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HIGH TEMPERATURE WORK

IN

IGNEOUS FUSION AND EBULLITION

CHIEFLY IN RELATION TO PRESSURE

BY

CARL BARUS

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ILLUSTRATIONS.

PREFACE.

In the following bulletin I have brought together the more important results of experiments in high temperatures, made since the publication of my bulletin on the thermoelectric measurement of high temperatures.[1] Chapter I, in addition to pointing out certain inherent relations between metallic vapor tensions, has a direct bearing on pyrometry. Chapters II and III are of geological importance, and the work was done for Mr. Clarence King. Chapter II shows that in case of the igneous fusion of basic magma, the passage from liquid to solid is one of contraction, and measures the difference of specific volumes at the solidifying temperature. Chapter III contains a full account of the thermal capacity of the same rock under the same conditions, and by aid of Chapter II leads to a numerical value for the relation of melting point to pressure, for silicates.

CARL BARUS.

JUNE 8, 1892.

[1] Bull. U. S. Geol. Survey, No. 54, 1889, p. 313.

HIGH TEMPERATURE WORK IN IGNEOUS FUSION AND EBULLITION, CHIEFLY IN RELATION TO PRESSURE.

By Carl Barus.

CHAPTER I.

THE PRESSURE VARIATIONS OF CERTAIN HIGH TEMPERATURE (METALLIC) BOILING POINTS.[1]

INTRODUCTORY.

1. *The plan pursued.*—In the following chapter[2] I describe a practical method for the calibration of thermocouples by aid of boiling points, and then apply it in measuring the vapor tensions of zinc, cadmium, and bismuth. During the course of the work a much neglected principle of Groshans[3] is advantageously employed. I must state at the outset that it is not at all my object to furnish accurate values for boiling points. The purpose of this paper is to investigate the probable nature of the relation of boiling point to pressure, throughout very wide ranges of temperature, with the hope of stimulating speculation on the subject somewhat more rigorous than that of Groshans. It is clear that if a law can be found by which the normal (76 centimeters) boiling point of a substance can be predicted from an observed low-pressure boiling point, then there is hope of arriving at a more complete knowledge of high-temperature boiling points than is now available. More than this: By varying pressure, boiling points may be made to overlap each other. Hence a thermocouple calibrated as far as the boiling point of zinc for instance, may be used to measure the low-pressure boiling point of bismuth (say), and the couple then may be further calibrated by making use of the normal boiling point of bismuth at 76 centimeters, predicted by aid of the law in question. The process may obviously be repeated. The couple whose calibration interval has been enlarged in the manner given, may now be used to fix the low-pressure boiling point of some

[1] The literature of the subject, which is very voluminous, may be omitted here because a full account is given in Bull. No. 54, pp. 1 to 30. At the present stage of progress of the kinetic theory of gases the air thermometer is still the only apparatus available for absolute high temperature measurement, and all data are directly or indirectly derived from it. An account of work of this kind is also given in the bulletin.

[2] Cf. Phil. Mag., (5), vol. 29, 1890, pp. 141–157.

[3] Groshans: Pogg. Ann., LXXVIII, p. 112, 1849.

other suitable metal, and then in turn be further calibrated by means of its boiling point. This is about the idea. It is not wholly illusory, as I think the present paper, which in spite of its approximate character contains considerable work, will show.

2. The pyrometer.—Let me say, too, that the platinum/platinum-iridium thermocouple used had on a former occasion[1] been tested for polymerization anomalies by minute comparison with the porcelain air thermometer,[2] and none were found. The alloy contained 20 per cent of iridium. M. Le Chatelier[3] unjustly rejects the platinum-iridium couple because of irregularities of the kind referred to. When the range of temperature is very large the Avenarius-Tait equation is found insufficient; but this equation subserves a good purpose when interpolation between two fixed temperature data, lying anywhere on the scale, but not very far apart, is called for.

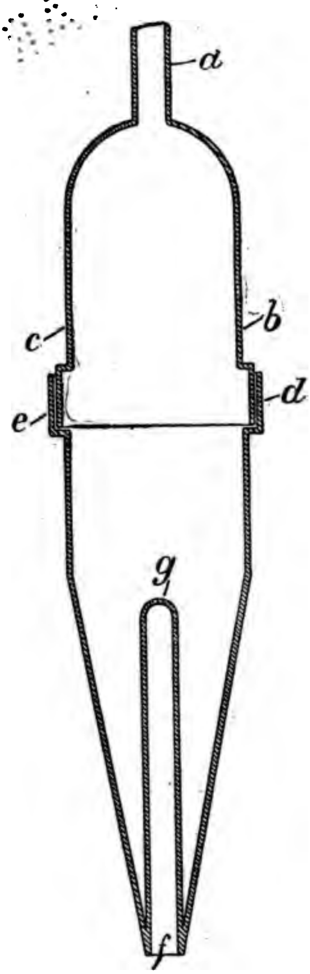


FIG. 1.—Boiling crucible for high temperatures. Scale, ½.

APPARATUS.

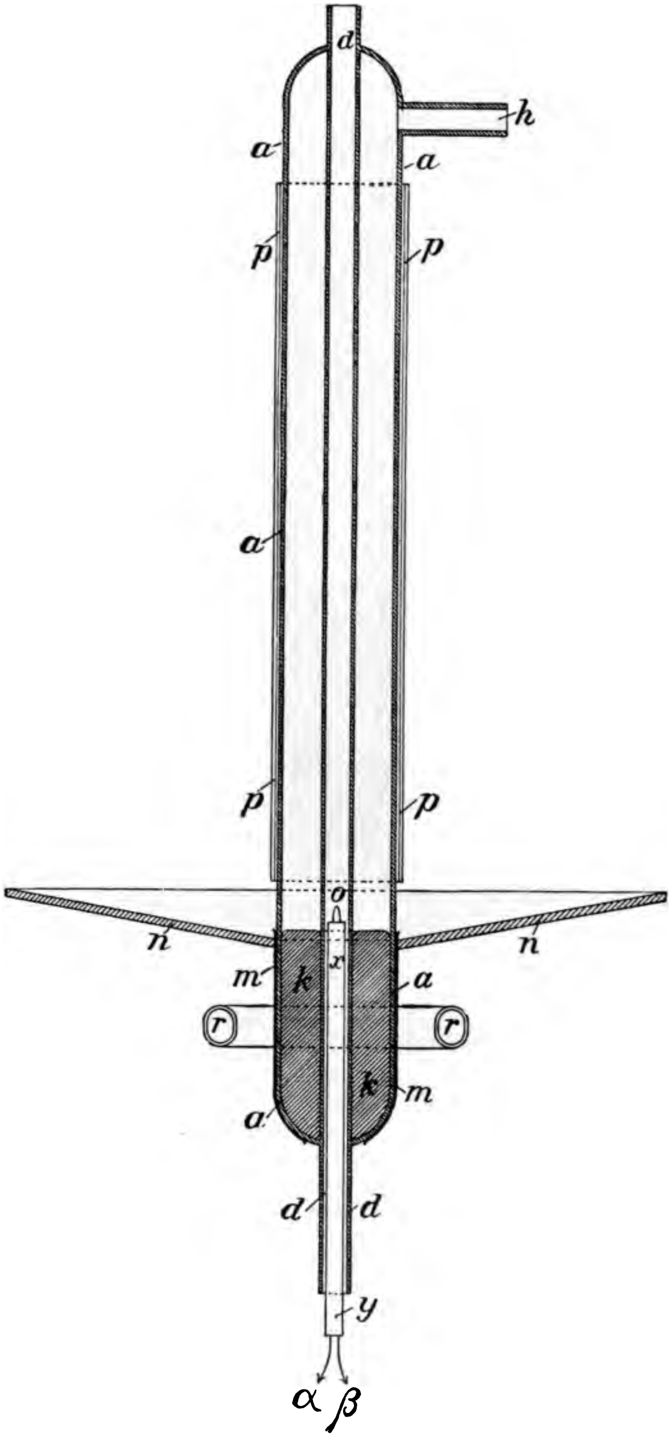
3. Low boiling points.—Boiling points below 500° may be studied in a closed glass tube *aa* (Pl. I), along the axis of which a thin-walled tube, *dd*, open at both ends, passes quite through. In the bottom of the annular space between the tubes the ebullition liquid, *kk*, is placed, and it is heated by the Gibbs' ring burner, *rr*. A funnel-shaped asbestos screen, *nn*, protects the upper tube against direct radiation. Other screens and jackets, *pp*, are suitably added. The upper end of the tube, *aa*, communicates with the air pump through the tubulure *h*. Finally, $\alpha\ \beta$, the thermocouple to be calibrated, consisting of platinum and platinum-iridium wire, is inserted into the bottom of the central tube, *dd*, with the junction *o* just above the plane of the ebullition liquid, *kk*. The upper part of the tube, *dd*, is closed with asbestos wicking (not shown), extending almost as far down as *o*.

The wires of the couple pass through parallel canals in a rod of fire clay, *xy*, and are thus well insulated. I may add that the boiling points

[1] Barus: Bull. U. S. Geol. Survey, No. 54, Chapter IV.

[2] Unfortunately circumstances did not permit me to make use of the former air thermometer comparisons, nor was it expedient to repeat the work.

[3] Le Chatelier: Bull. Soc. Chimique Paris, Vol. 45, 1886, p. 482. Cf. Phil. Mag., (5) vol. 34, 1892, p. 376.



BOILING TUBE AND APPURTENANCES FOR LOW TEMPERATURES. SCALE ½.

of mercury, sulphur, etc., for all pressures compatible with the strength of tube are conveniently obtained in this way. The vacuum boiling point of cadmium is also easily reached. Boiling may be kept up for any length of time.

4. High boiling points.—For boiling points above 500° it is more convenient to use glazed porcelain or fire clay crucibles of the form *efd*, *bdc*, (Fig. 1). The ebullition liquid is shown at *kk*, in Fig. 2, and *fg* is

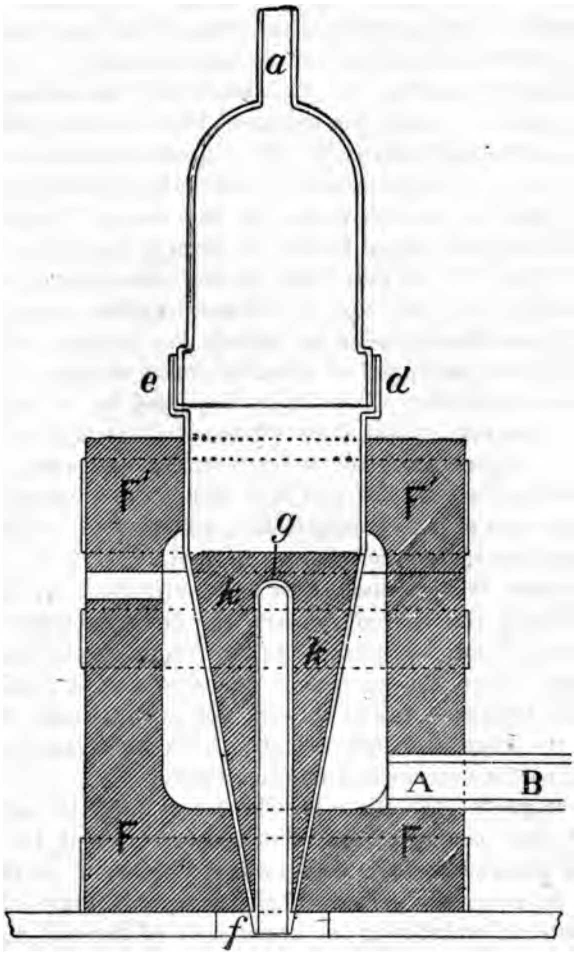


FIG. 2.—Furnace with crucible in place. Scale ½.

the central tube in which the thermocouple, *dd*, is to be introduced. To vary the pressure under which boiling takes place the tube *a* is connected with an air pump. Finally, a tight joint at *ed* is secured by calking with asbestos wicking, and then filling up with fusible metal the annular space or trough left above the asbestos.

The crucible, *efd*, is surrounded by a small furnace of Fletcher's composition, *FFF'F'*, Fig. 2, and heated with one or more blast burners, *AB*. If the flame impinges directly upon the cold crucible it is apt to break it; but such breakage may be quite prevented by surrounding the crucible with a conical shell of asbestos. Unfortunately, the crucibles can be used but once—unless the metal is cautiously poured out before solidifying, an operation which does not always succeed—for they are usually fractured by the solidifying metal, *kk*, on cooling. Nevertheless, the single experiment may be prolonged almost indefinitely; that is, for half a day or more. I found no difficulty in obtaining vacua of two or three millimeters at extreme white heat. In this case the crucibles must be well glazed internally. § 13.

5. *Torsion galvanometer.*—The best method of measurement is doubtless a null method, in which the thermoelectric constants are expressed in terms of a given Latimer Clark's cell. Recalibrations are then rarely necessary. But the computation of observations occurring in great numbers is somewhat inconvenient. In this respect the torsion galvanometer offers decided advantages. A form of apparatus of this kind is shown in Plate II, so that little further description will be necessary. *AA* is the coil of wire, and *BB* the astatic system seen in cross section. The system is suspended by aid of a fine platinum wire *EE;* and inasmuch as *AA* is wrapped on a heavy frame of copper, the motion of the needle is aperiodic. Torsion is imparted by aid of an alidade *DD*, and the amount registered by a large circle graduated in degrees. Fractions of a degree are read off by a mirror and scale adjustment, the parts of which are *C*, *MM* and *S*, *T* being the telescope.

The scale proper *ss* is on transparent glass, and *S* a white diffuse reflector, so that the scale may be more distinct.

The instrument is high enough to be manipulated by the observer standing. When the current passes, the deflected needle is twisted back to a fiducial position, parallel to the windings, and the amount at once read off. Then the current is reversed and a similar reading made. Since the resistance of the coil *AA* is practically the only resistance of the thermoelectric circuit, these deflections are directly proportional to the thermoelectromotive force.

The two magnets *BB′* Plate II, Fig. 1 and 2, of the astatic system each consist of a battery of four flat magnets, about 10 centimeters long, and of glasshard steel, consecutively annealed at 100° both for temper and for magnetic permanence.[1] A square frame of aluminium and hard rubber, embracing the upper half of the coil *AA*, connects the magnets. To this the adjustable mirror is attached. The torsion fiber is a platinum wire, .018 centimeter in diameter. It therefore has considerable strength to resist wear and tear. Finally, the plate-glass doors *xyz*, which close the magnet box, are easily removable, so that the magnet and mirror are conveniently accessible.

The instrument has two zeros: the optical zero of the mirrors, relative to which the reflected scale readings are symmetrical, and the

[1] Cf. Bull. U. S. Geol. Survey No. 14, 1885, p. 171. Cf. Chapter VI of the same bulletin.

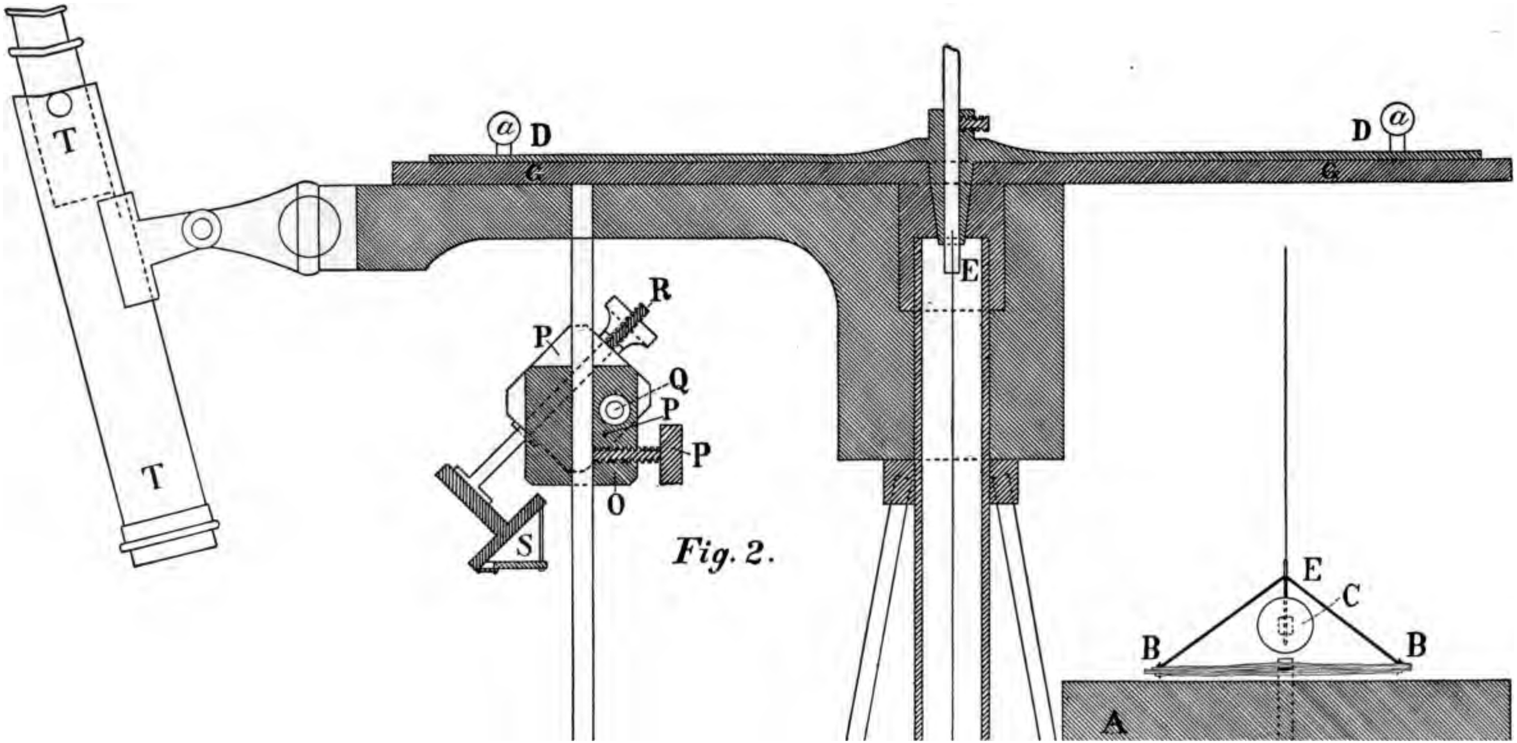
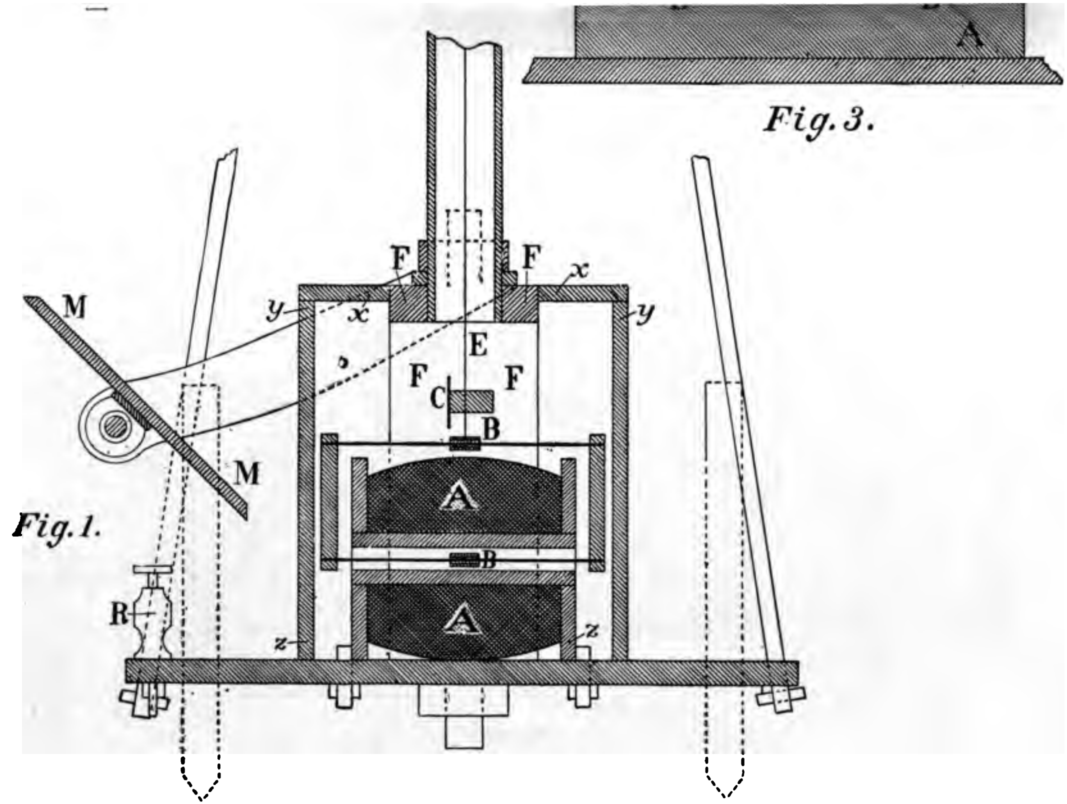


Fig. 2.



TORSION GALVANOMETER FOR THERMOELECTRIC PYROMETRY. SCALE ¼.

magnetic zero of the astatic system, relative to which the deflections are symmetrical. The two fiducial marks should coincide. The magnetic zero is shown by the fact that the mean of the scale readings on commutation coincide with the zero reading for no current. In case of a system of needles very nearly astatic, the optic zero may be determined by plotting scale readings in terms of twist registered by the alidade without current, and noting the position of symmetry in the circumflexed curve of the chart.

6. It will be seen that by bringing the needle back to zero by twisting the fiber, the effect of the earth's local magnetic field is almost wholly eliminated in an adjusted instrument For let u be the effective magnetic moment of the system and I the intensity of the current, τ the coefficient of torsion and φ the twist necessary to bring the needle back to zero. Then, apart from unnecessary constants,

$$I\,u + \tau\,\varphi=0;\ -\varphi=I\,u\,/\,\tau \qquad (1)$$

Again, in case of deflection φ' in a magnetic field of intensity H parallel to the coils,

$$I\,u \cos\varphi'+\tau\varphi'+H\,u' \sin\varphi'=0.$$

Supposing the deflections very small,

$$\varphi'=I\,u/(\tau+ H\,u') \qquad (2)$$

Now, in an incidental adjustment I found φ=4·35; φ'=4·00. Hence,

$$\frac{\tau}{H\,u'}=\frac{400}{35}\ .$$

In other words, the magnetic resistance is about one-tenth the torsional resistance to deflection by current. Now, inasmuch as deflections are used only to correct the torsion value, which is increased or decreased in single degrees, the effect of magnetic resistance is quite negligible. In measuring 100°, φ=4.35, and the correction must be less than ·6. Hence the magnetic resistance is less than ·06, or less than 1·5 per cent of φ. But inasmuch as the apparatus is primarily intended for temperatures greater than 350°, where $\varphi > 20°$, it follows that the magnetic resistance is usually quite negligible. A little care in the magnetization of the needle will produce the astatic condition much more fully than was done in the above experiment. The same relations apply for finer fibers, where twists are larger.

A few examples of the deflection D for 100° at the hot junction, in case of a thick platinum fiber (diameter .0055 centimeter), and variety of different magnetic fields may be added.

Factor.	D	Remarks.
·893	7·235 7·235	Strong field. Magnetic zero obtained by astasizing magnet.
3·45	7·324 7·319	Astatic needle. Fiducial zero obtained by twisting.
3·08	7·290 7·276	Astatic needle. Coils in its plane.
3·402	7·440 7·437 7·434	Astatic needle, kept in the plane of the coils by twisted fiber.

It follows finally that in the above instrument thermoelectromotive force is expressed only in terms of the torsion of a platinum fiber, supposing the needles to be so tempered and magnetized as not to change their magnetic permanence. Hence thermoelectromotive forces are not only expressed in terms of a fixed standard and therefore comparable with each other after the lapse of time, but the range of measurment is enormous. Any temperature between 100° and the intensest white heat may be measured without further adjustment. These desiderata, added to the convenience of manipulation, and the strength of the instrument against wear and tear, constitute the advantages of the galvanometer described.

In the practical form of this apparatus the torsion circle need not be more than 6 inches in diameter, accurately divided into degrees. The alidade should be provided with a lens. A silk fiber suspension may be put in the case xy, so that the needle may at any time be unhitched from the platinum fiber, and attached to the silk fiber. A magnetic position of equilibrium parallel to the coils is thus easily obtained.

Inasmuch as both the internal resistance of the coils, the magnetic movement of the needles and the elasticity of the platinum fiber change with temperature, the torsion galvanometer has a notable temperature coefficient. This, however, is determined at once by measuring the same temperature (hot junction) at two different temperatures of the galvanometer. The boiling point of mercury is a convenient datum for this purpose. Changes of temperature at the galvanometer are to be guarded against by placing a thermometer in the case.

7. *Cold junction.*—From what has been stated, if D be the amount of torsion corresponding in a given instrument to the temperatures T and t of the junctions of the given thermocouple,

$$D=a\,(T-t)+b\,(T^2-t^2)\ldots\ldots(1)$$

Again if $d=a\,(t-20)+b\,(t^2-20^2)\ldots\ldots(2)$

$$D_{20}=D+d=a\,(T-20)+b\,(T^2-20^2)\ldots\ldots(3)$$

Hence a small table corresponding to equation (2) is to be computed, from which the value of d for each value of t between 10° and 35° may be taken. A short preliminary calibration suffices for this purpose. In this way the observer may at once deduce D_{20} from D, where D_{20} is a function of T the temperature of the hot junction only.

By aid of the boiling points of water (100°), mercury (357°), sulphur (448°), cadmium (780°), zinc (930°), bismuth (1,500°), the quantity D_{20} may then be graphically constructed as a function of T, and the points between consecutive boiling points filled in by equation similar to (1).

From a chart of this kind the temperature T, corresponding to any degree of twist D_{20}, may be taken with facility.

OBSERVATIONS.

8. *Mercury.*—In the above apparatus the normal boiling point of mercury is sharply determinable; but there is considerable difficulty in

determining the low-pressure boiling points. Unless the heat be regulated to a nicety the lower layers boil under the pressure of the upper layers. Again, since the agitation of the liquid nearly ceases in approximate vacuo, a flame of moderate intensity presupposed, the rate of evaporation is retarded in relatively greater degree. In the case of a liquid of small specific heat, films of which do not adhere readily to glass, it is therefore to be suspected that both liquid and vapor will be superheated. On the other hand, if the flame of the burner be intensified so as to produce violent ebullition at low pressures, the liquid can be superheated to such an extent that its direct radiation on the junction of the thermocouple may heat it as much as 10° above the boiling point.

Accordingly I was not surprised that the temperatures obtained in the static method by Regnault, Hagen, Hertz, Ramsay and Young[1] are as a rule below the corresponding boiling points of the present dynamic method. It is only by taking great pains in the adjustment of burner and apparatus that my temperatures began to coincide with those of Regnault. But this nice adjustment introduces arbitrary conditions; hence low pressure mercury boiling points are to be rejected. At high pressures the unsatisfactory circumstances mentioned fall away; and the rate at which boiling point changes with pressure is enormously smaller.

In the following tables, 1 and 2, I give instances of my results. The data of Table 1 were obtained at an earlier date, before I became aware of the grave difficulties encountered. T is the boiling point for the pressure P, in centimeters of mercury:

TABLE 1.—*Boiling points of mercury (superheated)*

P	T	P	T	P	T
cm.	°*C.*	*cm.*	°*C.*	*cm.*	°*C.*
44·2	330	·5	194	0.3	198
37·5	325	6·4	256	0.3	184
17·5	290	12·0	280	0.1	183
1·0	195	25·2	310		
0·7	190	47·6	336		
0·5	176	76.2	356		
13·3	279	·2	199		
24·4	304				

In the following table are later results, obtained with great care, relative to the conditions stated at the outset of the present paragraph. The agreement with Regnault's data is very much better, but the temperatures are still high, particularly in the region of low pressure (cf. Fig. 2). D_{20}, the twist corresponding to T, has been added, to show the

[1] Ramsay and Young; Jour. Chem. Soc., vol. 49, p. 37, 1887; Landolt and Boernstein's tables, p. 56, Berlin, Julius Springer, 1883. I may advert in passing to a discussion between Messrs. Ramsay and Young and Kahlbaum. The former, corroborating Regnault's law, maintain that vapor tensions, whether obtained by static or dynamic mode of measurement, are identical. Kahlbaum believes that he has found a difference. Cf. Beiblätter, vol. 10, 1886, p. 485; ibid., vol. 11, 1887, pp. 88, 430.

delicacy of the apparatus, Pl. II, p. 14. Twist is expressed in degrees of arc:

TABLE 2.—*Boiling points of mercury (superheated).*

P	D_{20}	T	P	D_{20}	T
·1	8·10	164	·2	8·40	168
·2	8·10	164	·3	8·28	166
·2	8·11	165	·5	8·49	170
2·6	11·43	216	2·0	10·84	208
2·7	11·58	218	2·3	11·25	214
2·7	11·62	219	5·2	12·93	239
4·5	12·22	228	9·9	14·98	270
4·6	12·23	229	9·8	14·87	268
12·6	15·44	276	17·2	16·24	288
12·5	15·43	276	17·4	16·23	288
20·7	16·90	297	31·5	18·07	313
20·9	16·95	298	31·8	18·10	314
29·4	17·75	308	50·3	19·69	335
29·4	17·74	308	50·5	19·74	335
47·3	19·58	334	76·43	21·484	358
48·0	19·65	335			
48·5	19·75	336			
76·43	21·323	357			

9. *Sulphur.*—The behavior of sulphur is peculiar. On removing the pressure to about 1^{cm}, the substance soon passes into the treacle state, and the full ebullition observed under atmospheric and other pressures changes into a sticky frothing.

Exact temperature data can not, therefore, here be expected. The following table (3) is an example of the earlier results obtained:

TABLE 3.—*Boiling points of sulphur.*

P	T	P	T	P	T
cm.	°*C.*	*cm.*	°*C.*	*cm.*	°*C.*
·0	218	4·8	298	21·2	374
·0	205	7·0	316	39·8	410
2·4	263	11·2	337	76·0	448

The following table contains results of a later date, obtained by taking great care in guarding against superheating:

TABLE 4.—*Boiling points of sulphur.*

P	D_{20}	T	T *Regnault.*	P	D_{20}	T	T *Regnault.*
55·36	26·57	428	429	4·06	16·80	295	305
55·41	26·59	429	429	....	....	....	....
54·75	26·49	427	428	....	....	....	....
48·30	25·87	420	422	30·69	23·65	389	396
47·78	25·64	416	421	30·70	23·65	389	396
37·59	24·51	402	407	13·01	20·18	342	354
37·57	24·39	399	407	12·93	20·18	342	354
28·67	23·44	386	393	5·61	17·28	302	317
28·80	23·51	387	394	5·91	17·51	305	320
20·68	22·23	370	376	6·14	17·62	306	321
20·70	22·25	370	376	3·29	15·55	278	295
14·37	20·76	349	358	3·44	15·51	277	297
14·49	20·73	348	359	·75	10·76	206	252
11·15	19·66	355	346	1·05	11·33	215	*260
11·25	19·77	336	347	1·39	11·85	223	*266
6·11	18·05	313	321	1·67	11·21	228	*275
6·35	18·20	315	323	75·84	27·076	446	448
6·55	18·30	316	324	75·87	27·999	448	448

* Sulphur sticky.

These results agree fairly well with those of the earlier table. I have added the values of T, exterpolated graphically from Regnault's data, by aid of the Dupré-Bertrand equation. (Cf. § 14.)

$\text{Log } p = 19{\cdot}10740 - 4684{\cdot}49/\theta - 3{\cdot}40483 \log \theta$, which holds between $\theta = 663$ and $\theta = 843$ absolute degrees centigrade[1]. It will be seen by comparison of my values with the data predicted by this formula that it is much in error at low pressures. The divergence is largest in the neighborhood of 11^{cm}, and is here greater than 10°.

10. Zinc.—The following table contains data of four sets of experiments for zinc. The first of these were made in the glass tube (Fig. 1) at low pressures. Although in this case there was considerable volatilization, I did not observe any ebullition. In the table, the result marked * is the only datum of this work inserted. Change of temperature with pressure was not very obvious.

The remaining data of this part of the table are legitimate. The criterion of a boiling point is change of temperature with pressure. In the second and third parts of the table I aimed at greater accuracy. Each of the values given is a mean of two or three distinct measurements; † refers to a low position, ‡ to a high position of the thermocouple in the central tube (see Fig. 2).

TABLE 5.—*Boiling points of zinc.*

P	*T*	*P*	*T*	*P*	*T*
cm.	°*C*	*cm.*	°*C*	*cm.*	°*C*
1·0	*582	4·2	710	2·6	675
4·0	710	3·5	699	6·7	731
6·5	732	2·8	684	15·8	792
9·6	757	6·2	736	26·4	833
10·1	772	9·9	758	37·5	864
15·6	785	16·6	802	47·3	884
27·1	837	26·4	838	57·0	904
34·5	857	36·8	863	65·4	916
42·5	873	47·7	884	77·1	933
53·5	897	55·7	900		
76·4	933	65·3	914		
		77·3	†928		
		77·3	‡922		

11. Cadmium.—The first part of Table 6 contains results obtained in a glass tube. Ebullition in vacuum was obvious. But inasmuch as the limit of the power of the ring burner was not much above 500°, the remaining thermal data are too low.

The experiments of the second and third parts of this table were made in the porcelain crucible. They are legitimate, change of temperature taking place with every change of pressure. I was unable to make the crucible satisfactorily tight, so that mean values of fluctuating pressure had to be made use of. Again cadmium is more easily superheated than zinc; so that the present temperatures are probably high.

[1] I computed the inferior prolongation of the curve and plotted the results. From the chart the values of T were taken to a high degree of accuracy.

A repetition of the experiment failed in consequence of breakage of the crucible. It is interesting to note here that if zinc boils at 930°, cadmium will boil at a temperature not much below 780°.

TABLE 6.—*Boiling points of cadmium.*

P	*T*	*P*	*T*	*P*	*T*
cm.	°*C.*	*cm.*	°*C.*	*cm.*	°*C.*
·00	444	2·2	549	6·3	606
2·75	526	2·5	552	8·4	622
5·25	549	2·6	565	22·6	686
7·70	562	3·2	574	27·4	704
		7·5	620	34·2	722
		10·5	639	51·0	752
		15·7	667	56·3	760
		18·9	681	63·6	770
		26·2	702	65·6	772
		29·2	706	75·5	786
		35·5	724	75·5	788
		38·1	729	75·5	781
		48·9	745		
		51·7	750		
		62·4	760		
		64·4	766		
		65·6	766		
		75·6	772		
		75·6	770		
		75·6	774		

12. Bismuth.—Table 7 contains results for bismuth. In the first part of the table temperature does not change with pressure, hence a boiling point is not reached. In the second part of the table temperature certainly oscillates with pressure, hence the temperature corresponding to the lower values of pressure (3 to 4 cm.) are boiling points. The temperatures corresponding to the higher values of pressure (9 to 10 cm.) are below the corresponding boiling points, for I found that on further increasing pressure, the temperature did not increase. These temperatures are therefore at the limit of the heating power of the furnace. At least five minutes must be allowed for each observation. The top of the crucible, moreover, should be filled with asbestos, to diminish loss of heat by radiation.

TABLE 7.—*Boiling points of bismuth.*

P.	*T.*	*P.*	*T.*	Remarks.
cm.	°*C.*	*cm.*	°*C.*	
2·6	1152	3·2	1199	
5·8	1164	8·6	1211	
2·6	1165	9·7	1207	
8·1	1182	3·2	1206	
8·8	1186	3·7	1222	Flame intensified. B. P. criterion satisfied.
2·7	1183	4·2	1215	
9·8	1194	8·7	1247	
2·4	1186	3·9	1213	
		3·4	1204	
		9·5	1236	
		3·4	1207	
		4·0	1217	
		9·7	1260	
		3·4	1206	
		3·9	1221	
		9·6	1258	Limit of the heating power of the burner.
		3·3	1215	
		4·2	1233	

13. **Remarks.**—In the above tables, 1 to 7, the *criterion of boiling point* has therefore been change of temperature with pressure. When this was not observed, the data were rejected. The method of obtaining low boiling points from the liquid is doubtless objectionable, because of the liability to superheating. In special measurements made with zinc,[1] however, I found that the error thus introduced is negligible. There seems to be less superheating in case of metals and high temperatures, supposing the temperature of the environment to be reasonably near the boiling point (100° or 200° above it). In case of bismuth and metals of higher boiling points, the difficulties of experiment are such that I do not think a low pressure vapor bath is feasible.

In regard to the crucible used, I may remark that experimentation will be much facilitated by using tubular forms made in a single piece. In this case the trouble experienced in calking the joint of Figure 1 will be obviated. The metal, previously granulated, may easily be introduced through the tube *d*. In this case I have no doubt that very high vacua at white heat will be attainable. It is advisable, moreover, when very high temperatures are to be reached, to place the crucible and lid wholly within the furnace, allowing only a narrow tube to project out of it.

INFERENCES.

14. *Available equations.*—Equations for expressing vapor tension in terms of temperature have been invented in great number, and among them the simple form of Magnus and the more elaborate exponential devised by Biot and used by Regnault are given in most text books. A remarkably close fitting exponential is investigated and tested by Bertrand.[2] Quite recently M. Ch. Antoine[3] has proposed and applied a new form. Following the early suggestions of Bertrand[4] and of J. J. Thomson,[5] I have used the equation of Dupré,[6]

$$\log p = A - B / \theta - C \log \theta \qquad (1)$$

inasmuch as J. J. Thomson has given it an independent interpretation. The meaning of the equation is clearer in the differential form:

$$dp / d\theta = -p \ (C / \theta - B / \theta^2) \qquad (2)$$

or

$$d\theta / dp = \frac{\theta^2}{p} \frac{1 / B}{1 - (C / B)\,\theta} \qquad (3)$$

with reference to which it is to be observed that C / B is a small quantity (about 1/1000).

[1] Bull. U. S. Geol. Survey, No. 54, p. 109.
[2] Bertrand: Thermo dynamique, pp. 154 to 162, Paris, Gauthier-Villars, 1887.
[3] Ch. Antoine: C. R., CVII, p. 681, 1888; ibid., pp. 778, 836, 1888.
[4] Bertrand: loc. cit. p. 90 to 102.
[5] J. J. Thomson: Applications of dynamics, etc., p. 158, Macmillan, 1888.
[6] Dupré: Théorie mécanique de la chaleur, pp. 96 to 110, Paris, Gauthiers-Villars, 1869.

15. Constants computed.—Applying equation (1) to the results of the tables 1 to 7, I found the following set of values by direct computation:

TABLE 8.—*Constants. A, B, C, variable.*

Metal.	A	B	C
Mercury	+ 3·583	+3084	— 1·1371
Sulphur	—35·969	— 366·1	—13·066
Cadmium	—30·567	+1391	—11·180
Zinc	+42·265	+11435	+10·022
Bismuth	+24·774	+13495	+ 4·763

These results are grossly irregular, even as to sign. This might have been expected. To get comparable values for constants the observations in case of complex equations must either be very fine or in great number. Other direct methods gave similarly irregular constants, which need not be entered here. Nothing can be learned from them.

Bearing in mind, therefore, that it is my object to detect possible relations, and that my high-temperature boiling points are necessarily somewhat crude, I will facilitate preliminary computation by observing that in Dupré's data the prevailing value of A is nearly 20. Putting $A=20$ the following set of constants were obtained, in which, of course, there is greater degree of uniformity. Water has been added from Dupré:

TABLE 9.—*Constants. B and C, variable.*

Substance.	A	B	C
Water	20·324	2795	3·868
Mercury	20	4345	4·013
Sulphur	20	4379	4·217
Cadmium	20	7467	3·643
Zinc	20	8433	3·603
Bismuth	20	12561	3·456

The results of this table are encouraging. From an inspection of the constants I was led to suspect better agreement in making C constant and A variable. This step is further suggested by assuming, conformably with the indications of table 9, that for any two substances, S and S', the boiling points, θ and θ', corresponding to a given pressure, p, will follow the relation $B / B' = \theta / \theta' = n$, where n is constant for the given pair of substances. This virtually postulates a fundamental equation of the form (1) from which all others are derived by substitution, as follows:

$$\log p = A - B/\theta - C \log \theta \qquad (1)$$

$$= A - nB/n\theta - C \log n\,\theta + C \log n$$

$$= A' - B'/\theta' - C \log \theta' \qquad (4)$$

The constants of Table 10 are obtained by supposing C to be constant for all the substances. As to the choice of a value, I noticed that the mean C of Table 9 is almost identical with Dupré's C for water. Hence it was chosen.

TABLE 10.—*Constants A and B, variable.*

	A	*B*	*C*
Water	19·324	2795	3·868
Mercury	19·029	4396	3·868
Sulphur	19·776	4458	3·868
Cadmium	20·63	7443	3·868
Zinc	20·98	8619	3·868
Bismuth	21·51	12862	3·868

The constants might be much improved by successive trials; but further work would be wasted.

16. Graphic representation.—In order to clearly exhibit the point of view I have taken, it will be necessary to plot these results graphically. This is done in Plate III, in which the abscissæ are pressures in centimetres of mercury and the ordinates boiling points in degrees centigrade.

The curves passed through the observations are computed for the constants of Table 8. Some points computed by Table 9 are marked; points computed by Table 10 are also marked. The agreement of observed and computed results is quite within the errors of observation, as will at once be evident from an inspection of the chart. In case of mercury I have added the vapor tension results of Regnault, showing that they are uniformly lower than the present data. The reasons have already been given in § 8.

The results for bismuth are particularly interesting. Unfortunately it was impossible for me to calk the crucible tight enough, in order that the low-pressure boiling point of bismuth might overlap the normal boiling point of zinc, which limits the calibration interval of the thermo-couple. The chart shows that the interval of extrapolation is about 270°. This makes the bismuth results less certain. For this reason, perhaps, the normal boiling point of bismuth, as deduced by Groshans's principle is too high, being 1550°. Carnelley and Williams,[1] using a calorimetric method, obtained only 1450° as their maximum value. It is probable, however, that the radiation errors in Carnelley and Williams's experiments would tend to make their data too low; nor have they any sure criterion that ebullition had actually set in. In experiments of my own,[2] using a Fletcher furnace with three blast burners, I signally failed to boil bismuth in a number of trials. The boiling-point criterion in the present results is beautifully exhibited: When pressure increases the group of points *B* on the chart pass into the group of points *A*; hence the group *B* are boiling points. When pressure increases further the group *A* does not increase in temperature; hence group *A* are not boiling points, but merely indicate the maximum heating power of the furnace.

17. Conclusion.—I am perfectly aware that the method pursued above, in endeavoring to reach perspicuous results, is forced. Ber-

[1] Carnelley and Williams, Journ. Chem. Soc., London, vol. 35, 1879, p. 565.
[2] Bull. U. S. G. S., No. 54, pp. 116–118, 124.

trand computes the constants of Dupré's formula for 16 substances, and shows its admirable agreement with the observed data throughout. But the constants in such a case vary largely: A between 4 and 21 (pressures being expressed in centimeters of mercury); C between -9 and $+5$. In any such grouping of constants as I have attempted, the agreement of the formula would therefore be lost. It is worthy of remark, however, that in 10 out of the 16 substances A lies between 15 and 21·5, and in one-half of the substances C lies between 3·2 and 4·2.

When, however, the errors left in any attempt to group the constants are considered, not so much with reference to the small range of temperatures of a single substance, but rather with regard to the relatively enormous range of temperatures exhibited by these phenomena as a whole, and by a diagram, such as Pl. III, for instance, then the errors in question assume much smaller importance. In the above pages I have presumed to believe that at the outset the wide temperature comparison is the one which ought first to be made, and some fundamental relation applicable to the whole range of temperature investigated. After this has been done, the said relation may then be modified to suit the individual and exceptional case.

I can state this more clearly as follows: Groshans's derivation of his principle is sufficiently simple; for, if vapors have identical coefficients of expansion, 1/273, say, and their densities be expressed relatively to the density at the normal boiling point in each case, then the ratio of absolute boiling temperatures corresponding to any two given pressures will be the same for all vapors. This inference is incorrect just in proportion as the application made of the Boyle-Charles law is incorrect.

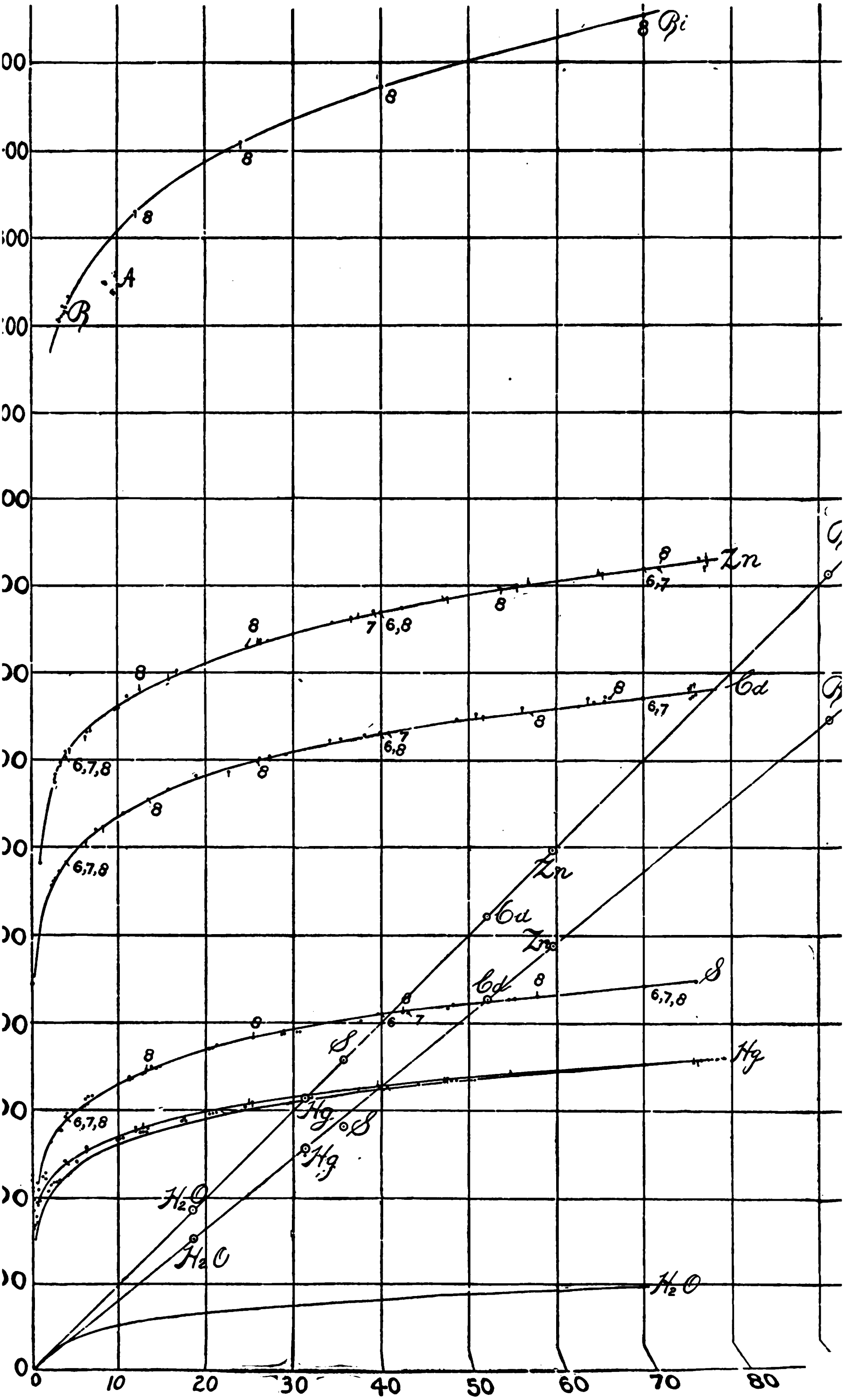
However, Dupré in deriving his formula makes virtually the same assumption.[1] Again, J. J. Thomson[2] introduces Boyle's law into the mean value of the Lagrangian function investigated for the present phenomena. Inasmuch, however, as the forms of two arbitrary functions have here to be determined by experiment, the insertion of Boyle's law suffices Thomson's purposes. Following the model of his work, I hoped to find some suggestion as to the modification of Dupré's equation, such that it may be the outcome of an original type for all substances, by inserting Van der Waals's law, $p=R\Theta/(v-b)-a/v^2$, instead of Boyle's law into the proper term. It seemed plausible that Dupré's equation could thus be corrected by aid of constants, the molecular interpretation of which has already been given by Van der Waals. Performing the operations, I find, rigorously,

$$R\theta\log\frac{\rho_0}{\rho}\frac{\zeta-b\rho}{\zeta-b\rho_0}=-R\theta\left(\frac{\zeta}{\sigma}\frac{\rho}{\zeta-b\rho}-b\frac{\rho_0}{\zeta-b\rho_0}\right)+\frac{a\rho}{\zeta^2}\frac{\rho-\sigma}{\sigma}+(w-w')-\Psi(\theta)$$

where a and b are Van der Waals's constants. This equation, though capable of simplification, essentially involves ζ, and is therefore not suggestive.

[1] Bertrand: loc. cit., p. 101.

[2] Thomson: loc. cit., p. 158.



HART SHOWING THE CHANGE OF BOILING POINT WITH PRESSURE (CENTIMETERS OF

CHAPTER II.

THE CONTRACTION OF MOLTEN IGNEOUS ROCK ON PASSING FROM LIQUID TO SOLID.

INTRODUCTORY.

18. The rock.—The following volume measurements were made for Mr. Clarence King, on a sample of diabase which he furnished. The object thus far is to develop the general character of the expansion phenomenon, and for this reason a fusible rock, without action on hot platinum, was selected. In future researches, graded rock magmas, passing from extreme acid to extreme basic, will be operated on.

19. Literature.—The importance of the question is well known, but a literary discussion is superfluous here, since Prof. F. Niess[1], of Hohenheim, not long ago made a careful survey of all that has been done on the subject. The reader desiring specific information is referred to this interesting pamphlet. "Es ist ein durch Contraste buntes Bild," says Prof. Niess (loc. cit., p. 36), "welches in der vorstehenden Citatenlese dem Leser zu entrollen war, und aus dem Wirrwarr entgegengesetzter Ansichten heben sich nur zwei Körper: Wismuth und Eisen, heraus, über welche man wohl mit absoluter Sicherheit die Acten als geschlossen bezeichnen kann, und zwar in dem Sinne, dass für sie die Ausdehnung im Momente der Verfertigung als zweifellos bewiesen gelten kann. Die übrigen Metalle stehen noch im Streit, und für sie gilt das Gleiche was wir für die künstlichen Silicate zu fordern hatten * * *" Now, iron, in virtue of the occurrence of recalescence (Gore, Barrett), is scarcely a fair substance to operate upon, and it heightens the confusion to find that Prof. Niess, after carefully weighing all the evidence in hand, is obliged to conclude that rocks expand on solidifying.

The present experiments show beyond question, I think, that at least for diabase this is not true. I find that this rock not only contracts between 3.5 to 4 per cent on solidifying, but that such solidification is sharp and only apparently continuous, and that the fusion behavior throughout is quite normal in character. Hence with certain precautions which I shall specify in the course of this paper, §21, the volume thermodynamic relations which I deduced by acting on organic bodies may be applied to rock magmas.

20. Effect of fusion (polymerism).—The rock after fusion is changed to a compact black obsidian and quite loses its characteristic structure.

[1]Niess: "Ueber das Verhalten der Silicate, etc.;" Programm zur 70. Jahresfeier d. k. Würtemb. landw. Academie. Stuttgart, E. Koch, 1889.

It was therefore important to examine the volume relations of this change preliminarily. This is done in Table 11, where the densities obtained with lumps of the rock (mass M), at the temperature t, are given, Δ being the density before, Δ' after, fusion.

TABLE 11.—*Density, Δ, of the diabase, before and after fusion. Massive pieces (not ground).*

A.—BEFORE FUSION.

Sample No.	M	t	D	m	d	Δ	$\frac{\Delta-\Delta'}{\Delta}$	Remarks.
	g	°C						
I	22·8950	25	....	....	....	3·0161	....	
II	45·3654	21	....	....	....	3·0181	....	
III	54·7208	21	....	....	....	3·0136	....	
IV	69·4940	21	....	....	....	3·0235	....	

B.—AFTER FUSION.

Sample No.	M	t	D	m	d	Δ	$\frac{\Delta-\Delta'}{\Delta}$	Remarks.
I	60·9330	21	....	....	....	2·7018	·104	Fused in clay crucible. Lump broken out when cold.
II	33·7659	19	3·5013	11·1686	21·021	2·7447	·090	Fused in a platinum crucible.
III	29·9777	19	3·5496	11·2712	(21·00)	2·7045	·103	

The rock was fused both in clay and in platinum crucibles. In the latter case the density d of the known mass m of the platinum crucible had been previously determined, and D denotes the observed density of molten rock and crucible together after fusion. In the case where a clay crucible was used, this was broken away from the glass within and the density of the solid lump (glass) then measured directly.

A few small air bubble cavities were visible on the fresh fractured surface of the glass, due, I presume, to the possibility that most rocks, like most organic liquids, hold gases in solution, which separate on solidification. At some other time I will make sharp vacuum measurements of the density of ground powders both of the rock and of the glass, but I do not believe the results of Table 1 will be seriously changed by such a test.

From Table 1 it appears that the mean density of the original rock is 3·0178. That of the glass after fusion is 2·717, showing that the result of fusion has been a volume increment of 10 per cent. This remarkable behavior is not new nor isolated. Niess (l. c., p. 47), quoting from Zirkel's Lehrbuch, shows even more remarkable volume changes of the same nature in garnet, grossularite, vesuvianite, adularite, orthoclase, augite; but I doubt whether the great importance of this behavior has been sufficiently emphasized. Suffice it to indicate here that it makes an enormous difference into what product the magma is to be conceived as being solidified, and that throughout this paper the molten rock solidifies into an obsidian. I am really only determining, therefore, those volume changes which lie at the margin, as it were, of the more profound but chemically structural volume change, which latter may be reasonably conceived as producible by pressure alone under conditions of nearly stationary (high) temperature.

I may add in passing that, from the magnitude of the chemical change, I shall carry my work on the effect of pressure on chemical equilibrium of solids and liquids and on the solution behavior "solid-liquid" into greater detail than I have hitherto attempted.[1]

APPARATUS.

21. Temperature measurement.—In work of this kind, an apparatus for the accurate measurement of high temperatures is the fundamental consideration. I may, however, dismiss this subject briefly here, since I discussed it elaborately in Bulletin No. 54, U. S. Geological Survey. The temperature measurements of this paper were made with thermocouples of platinum and platinum with 20 per cent of iridium, and they had been frequently calibrated by aid of the porcelain air thermometer within an interval of 1100° and tested for freedom from anomalies beyond that interval. Reference to the bulletin cited will show how thoroughly reliable this thermocouple is. Inasmuch as the process consists in expressing thermoelectric force by aid of a zero method in terms of a given Latimer Clark cell, the temperature apparatus is of the same order of constancy as to time as the standard cell.

In order to find, however, how far this work was trustworthy after a lapse of more than four years since it was done, I made fresh check measurements of the boiling points of mercury and of zinc. The latter need only be cited here. My original datum of the boiling point of zinc expressed as thermoelectric force for the couples under consideration was e_{20} = 11,074 microvolts, the cold junction being at 20° C. The new experiments referred to gave me data as follows:

	Microvolts.
Thermocouple No. 35	e_{20} = 11, 168
No. 36	= 11, 127
No. 39	= 11, 116
No. 40	= 11, 136
Mean	= 11, 137

agreeing very closely with two subsequent, specially careful measurements, viz:

	Microvolts.
No. 36	e_{20} = 11, 131
No. 39	= 11, 134

Thus the difference of values new and old is only 60 microvolts about ½ per cent as regards electromotive force, corresponding to something over 4° at 1000°. In view of the excessive use and abuse to

[1] Am. Journal, vol. 37, p. 339, 1889; ibid., vol. 38, p. 408, 1889; ibid., vol. 40, p. 219, 1890; ibid., vol. 41, p. 110, 1891; ibid., vol. 42, p. 46 et seq., 1891; Phil. Mag., (5), vol. 31, p. 9, 1891.

which the couples had been put in the meantime, this result is in itself gratifying.

Endeavoring to find, however, where this discrepancy was to be sought, I also made fresh comparisons between the Latimer Clark standard and a normal Daniell of my own (bulletin cited, p. 100), in which the two cells are separate and only joined (with zinc sulphate solution) during the time of use. Supposing the Latimer Clark cell to have remained constant the succession of following values was found:

March,	1886, 20° C., L. C., $e = 1{\cdot}435$		Daniell, $e = 1{\cdot}138$
August,	1887, 28° C.,	1·435	1·139
September,	1891, 27° C.,	1·435	1·147

If, therefore, instead of regarding the L. C. cell constant, I had assumed the Daniell as constant[1], the thermoelectric difference for the interval of four years would be wiped out. Now my L. C. cells were made by me in 1883, when less was known about the subject than is now available[2]. I conclude therefore that the discrepancy is very probably in the standard cell employed and that my thermocouples have remained absolutely constant.

Apart from this, the new standardization by aid of the boiling point of zinc fixes the scale irrespective of surmises or hypotheses, assuming that zinc boils at 930°.

22. General disposition of apparatus.—This is given in Pl. IV, on a scale of ½, where figures 1 and 3 form a sectional elevation showing the parts chiefly with reference to their vertical height, and figure 2 a sectional plan in which the parts are represented with reference to the horizontal.

The molten rock *ZZ* contained in a long cylindrical platinum tube, largely surrounded by a tube of fire clay, *FF*, is fixed vertically in a long cylindrical furnace, *DD LL*. The heat is furnished by six burners, *BB*, fed by gas and an air blast laden, if need be, with oxygen. These burners are placed at equal intervals along the vertical, three on one side and three on the other (Pl. IV, Fig. 2), and set like a force couple so as to surround the platinum tube with a whirlwind of flame. Suitable holes are cut in the walls of the furnace for symmetrical insertion of the insulated thermocouples, *T*, and also at *S*, for fixing the sight tubes, *A*, near the top and the bottom of the furnace. Parts of the envelopes of the platinum tube are cut away, so that its upper and lower end can be seen in the telescope of an external cathetometer. Thus the expansion of the platinum tube is measured directly. A vertical micrometer, *Kkd*, Pl. IV, Figs. 3 and 4, insulated so as to admit of electrical indications of contact, furnishes a means of tracing the apparent expansion of the rock *ZZ*.

In principle the operations are so to be conducted that under the conditions of slow cooling the magma may be relatively much less

[1] Our laboratory affords no means for the direct measurement of electromotive force.

[2] See Lord Ragleigh in Phil. Trans., June, 1884, and Jan., 1886; also Carhart, Am. J. Sci., Nov., 1884.

viscous than the practically rigid platinum envelope throughout the work.

The furnace stands on a massive iron base perforated with eight holes, into which vertical iron uprights are screwed, symmetrically surrounding the furnace and at a distance of 4 or 5 centimeters from its circumference. Only one of these is indicated, in part, at *QQ*, in Pl. IV, Fig. 3, the rest with other subsidiary parts being omitted to avoid confusing the figure. Two of these uprights hold the vertical micrometer, two others hold the burners in place. To the fifth the sight tubes are adjustably attached, to the sixth the thermocouple insulators are clamped exteriorly to the furnace, and the remaining two fix the clay holders *H*, *H*, by which the tube *FF* is adjusted vertically. All of these uprights are hollow, and a current of water continually circulates through them with sufficient rapidity to issue finally still cold to the touch. In this way the observer is able to move and change the accessories of the furnace with comfort even when the temperature within is maintained at 1500°. A single stream of water is sufficient, the ends of the uprights being joined by rubber tubing, and this same current additionally flows through the screen *XX* of the vertical micrometer and the high vertical screen of the cathetometer.

23. The furnace.—It should be added to the remarks made in the preceding paragraph that all the burners *B*, *B*, Pl. IV, are fed by the same amount of gas and air by properly branching the large supply tubes. A graduated stop cock is at hand for regulating the supply of gas to a nicety, whereas the air blast need not be regulated. Hence the furnace is fed with a mixture of gas and air, and temperatures from 1600° to 400° may be obtained by simply making the influx richer or poorer in illuminating gas. Burner constructions suitable for this purpose are given in Bulletin No. 54, p. 182. For higher temperatures the blast may be made richer in oxygen, but I have thus far had no need of doing this.

The products of combustion are carried off by the two oblique tubes *E*, *E*, in the lid *LL*. Note that the water screen bends around the vertical micrometer in such a way that flames issuing from *E* can do no injury. The central narrow hole in the lid *L*, through which the end piece *dd* of the micrometer passes, is closed by a free plate of fire clay *mm* perforated so as to surround *dd* loosely.

The blast was furnished by a pair of large-sized Fletcher bellows, each with three sheets of rubber above the reservoir. These bellows were set so as to form a double-acting pump, and actuated by aid of a short crank on the axle of a small gas engine. The blast pressure so obtained is considerable, a requisite in the above instances. It can be regulated by lengthening or shortening the crank, whereby the arc of reciprocal motion of the bellows is increased, the frequency remaining unaltered. The efflux pipes of both bellows discharge into a common gas pipe leading to the furnace.

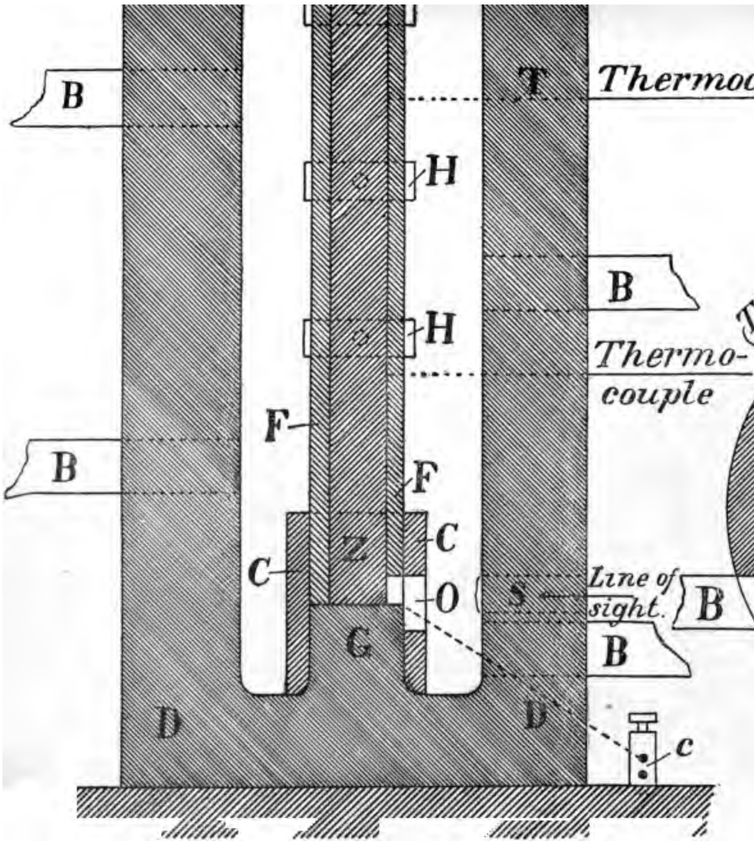
In order to obtain greater constancy of temperature and increase the high temperature efficiency of the furnace at the same time, it is essential to jacket the furnace, *DD*, and lid, *LL*, externally with a coating of asbestos fully ½ inch or more thick. I noted that in these cases the clay parts of the furnace became red hot throughout, whereas the uncovered furnace is not much above 400° externally. This indicates a smaller loss by radiation in the former case.

24. Fusion tube.—The platinum tube holding the molten rock, *ZZ*, Pl. IV, was 25 centimeters long and 1·5 centimeters in diameter, with walls about ·02 centimeter thick. It was drawn as accurately cylindrical as possible, and the bottom was plane and at right angles to the axis. To protect this tube from gases and to keep it from bulging in consequence of the pressure of rock within, the platinum tube is surrounded by a fire-clay tube, Pl. IV, *FF*, Figs. 1 and 6, fitting loosely. Care must be taken to allow for shrinkage. Thus a fresh clay tube, after about two hours heating at 1500° shrank from a length of 25·4 centimeters to 24·6 centimeters, i. e., ·8 centimeter or more than 3 per cent. This shrinkage is permanent and uniform in all directions, and is not, therefore, due to viscous sagging; after its full value has been reached, moreover, it ceases and the tube expansion is then normal. If properly sustained in the furnace the clay tube *FF* does not bend or warp. The holders, which I found very serviceable for this purpose, are shown at *H*, *H*, in Pl. IV, Figs. 1, 2, and 7. They are made of fire clay and held in position by suitable clamps on the outside of the furnace (not shown). In this way the fusion tube is to some extent adjustable.

The bottom of the tube, *FF*, is additionally fixed by aid of a perforated fire-clay ring, *CC*, Figs. 1 and 5, which embraces both the tube, *FF*, and a projection in the furnace, *G*.

25. Thermocouples.—These are three in number and inserted through the walls of the furnace, *DD*, Plate IV, in the positions given at *T*, in Figures 1 and 2. But Figs. 6 and 8 give a fuller account of the adjustment. The tube, *FF*, is laterally perforated with three pairs of fine holes, *t*, *t*, *t*, corresponding to the two canals in the insulator, *TT*. The wires of the thermocouple are then threaded through *t*, and the insulator in such a way that the junction lies in a small cavity at *t*, immediately in contact with the platinum fusion tube. A hole is cut in the tube, *FF*, opposite *t* (see Pl. IV, Fig. 8) and a similar one in the opposite wall of the furnace to facilitate these operations, the platinum tube being for the time removed. The advantage gained in this way is two-fold, since in the first place no part of the wires of the couple are directly surrounded with flame, and there is no danger of an accidental contact of these wires on the outside of the tube, *FF*. It is known that in the presence of carbon there is danger of passing silicon into the platinum, making the metal relatively fusible. Now, even if the hot gases of the furnace are reducing, they are to some extent stagnant in the insulating tubes, whereas in the flame they are constantly renewed. This I attribute to the protecting effect of the insulators.

The cold junctions of the thermocouples terminate in three pairs of mercury troughs, insulated by hard rubber, and submerged in a bath of



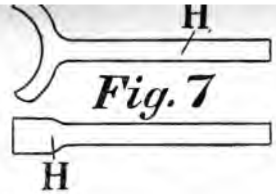


Fig. 7

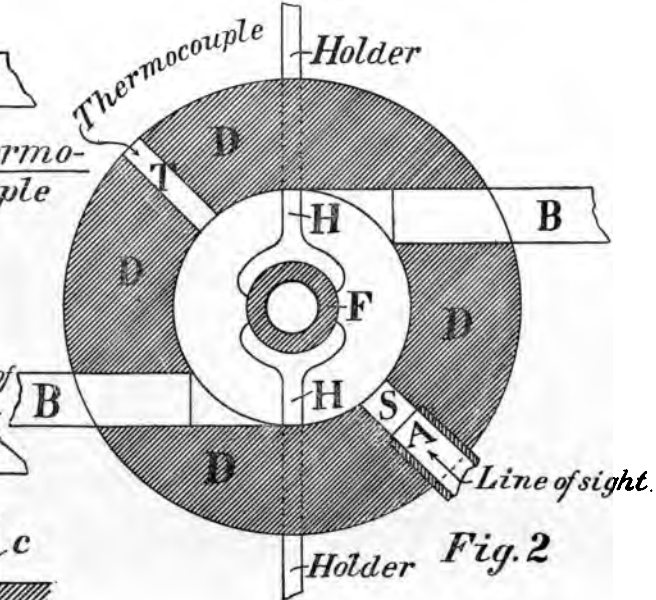


Fig. 2

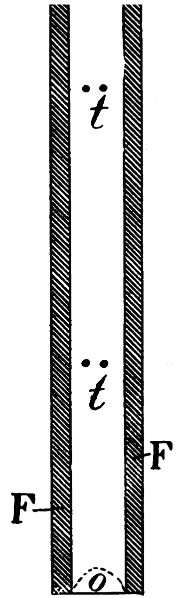


Fig. 6

petroleum. With these troughs the terminals of the zero method, § 21, are connected at pleasure, so that the temperatures at the top, middle, and bottom of the fusion tube are easily determined. Data are given in full below.

26. Sight tubes.—It has been stated, § 22, that the increase of length of the platinum fusion tube, *ZZ*, is to be measured directly. For this purpose Grunow's excellent cathetometer is placed on a suitable pier on the outside of the furnace, so that the prism of the instrument is only about 50 centimetres off from the platinum tube. To obviate the hurtful effect of radiation, however, a tall, flat water screen, 30 centimetres broad, 70 centimetres long, and 1 centimetres thick, and movable on a slide, is placed between furnace and cathetometer. Slots closed by plate glass are cut through the screen to correspond to the two positions of the telescope, and the furnace walls, *DD*, are similarly perforated, at *S*, above and below (see Pl. IV, Figs. 1 and 2), so that the ends of the platinum tube may be seen. The top of the latter projects above *FF;* but this tube and the ring, *CC*, are perforated at *O*, as shown in Figs. 1, 5, and 6. When the furnace is red hot within, the end planes or lines stand out very sharply against the red-hot clay background, in consequence of a difference in the emissive power of the metal and the clay, and hence the measurement is possible with the necessary degree of accuracy.

It is essential, however, to prevent the escape of flame and gas at *S*, and this may be done by closing these holes with sight tubes (only one of which is shown, *A*) of porcelain and about 15 centimeters long. The outer end of these is ground off square and a plate of plate glass, *b*, held against it by aid of the clamping device, *aa*. Surrounding the porcelain tube, *A*, with a layer of asbestos, and cutting a thread on the inner face of the brass ring, *a*, the latter may be screwed on to the soft asbestos, and then serve to secure an iron ring by aid of two machine screws, as shown. The iron ring holds the glass plate, *b*, in place. This joint should be well made, for if there is an escape of hot gases here, the glass is apt to break, though I have had no serious accident of this kind. At first, drops of water collect on *b*, but they disappear as the temperature rises.

27. Vertical micrometer.—Figs. 3 and 4, Pl. IV, give a full account of this instrument, both of which are sectional elevations at right angles to each other. A good millimeter screw, *Kk*, plays easily through the massive block of brass, *PP*, and the fixed lock nut, *gg*, and *l* is the vertical millimeter scale whereby the motion of the graduated head is registered. The block, *PP*, is bolted down to the thick bridge of brass, *NN*, by means of the screws *R*, *R*, and the counter plate *UU*. The ends of *NN* are provided with sleeves, *pp*, and a clamp screw *M*, so that the whole micrometer may slide up or down, or be clamped in any vertical position on the uprights, one of which is indicated at *QQ*.

It has been stated that the registration of the micrometer is to be electric, and hence the screw, *Kk*, must be insulated. This is done by surrounding the screws *R*, *R*, with a layer *n*, *n*, of hard rubber, from which the ends alone project, and insulating the plate, *PP*, and the counter plate of brass *UU*, by interposed sheets of hard rubber *jj*, *ii*, and the washers *q*, *q*.

In order to provide for a certain amount of horizontal adjustment of the micrometer, sufficiently wide slots are cut in the brass bridge *NN*, (see figures) whereby the plate, *PP*, may be shifted about 1 centimetre in any direction and then clamped in position.

In view of the heat which continually rises from the furnace, a V-shaped screen, *XX*, through which water rapidly circulates, nearly envelopes the micrometer below. Water enters and issues through tubes *V* and *Y* at diagonally opposite corners of the top of *XX*. Inasmuch as the micrometer screw, *Kk*, passes through a narrow hole in the bottom of *XX*, this screen must also be capable of lateral adjustment, and this is easily accomplished by aid of two vertical screw hangers *h*, *h*, soldered to *XX* below and passing through wide slots in *NN*, to which they are secured in any horizontal or vertical position by suitably flanged nuts above and below *NN*. Thus it is seen that the micrometer and its water-screen slide as a single piece along the upright *QQ*, an arrangement which greatly facilitates the final adjustment. *Q* and *Y* are connected by a sufficient length of rubber tube, as is merely indicated in the figure. There is a like connection on the other side.

Finally, the end of *Kk* is prolonged by a straight cylindrical tube of platinum *dd*, which may be fixed to the steel rod *k* by aid of the clamp *e* in any position along the vertical. This tube *dd* fits the rod *k* snugly, and should it become bent or warped by accidents, a special steel rod is provided by means of which it may easily be straightened again.

The lower end of *d* is clearly visible in the telescope of the cathetometer through the sight tube *A*. On being screwed down it enters the fusion tube *ZZ* axially, supposing the micrometer and fusion tube to have been properly fixed in position. In how far this has been done can always be seen by temporarily removing one of the efflux pipes *E*, Pl. IV, Fig. 4, when the end of the fusion tube and the motion at the lower end of *d* is visible to the eye. On actuating the micrometer head of *Kk*, the lower end of *d* should show but slight lateral motion in the telescope. Usually the tube *d* becomes coated with an enamel of molten rock, but this is of no consequence, since the increase of length is noted in the measurements.

28. *Telephonic registration.*—Since it is the object to find how far the meniscus of molten rock *ZZ*, Pl. IV, lies below the plane of the top of the fusion tube, the moment of contact of *ZZ* and *d* is best registered electrically. So long as the interior of the furnace is red hot, the rock is a good electric conductor. Hence, if a current be passed into the screw *Kk*, at the clamp screw *f*, Pl. IV, Fig. 3, it will issue at the bottom at the clamp screw *c*, Pl. IV, Fig. 1, provided, of course, *c* be electrically

connected with the bottom of the fusion tube. This is easily done by placing the fusion tube on a plate of platinum above *G*, and connecting this with *c* by means of a platinum wire, as is indicated in the figure.

It is, however, very convenient to register the contact of *ZZ* and *d* telephonically, and this may be easily done by using the intermittent current of a small inductor like that of Kohlrausch. Contact then evokes a loud roar in the telephone, and the observer's attention is not further distracted. The adjustment is quite delicate, and if the glass *ZZ* be sticky, the drawing out of a thread is indicated by a gradual cessation of the noise in the telephone, etc. In fact, the character of the fusion may be pretty well inferred in this way. The instrument is available almost as far as 400°, at which time, however, the furnace is dark, and cathetometric measurement is no longer possible.

Care should be taken to secure small sparking distances, for this quantity will vary with the temperature of the gas in the furnace.

If the expansion of the rock be known, and the tube *dd* sunk deeply into the mass, it is clear that the present method admits of a measurement of the relation of electric resistance and temperature. I mention this, believing that a suitable method for temperature measurement may be thus available.

Elsewhere[1] I have already speculated on the character of the changes of electrolytic resistance referred to temperature. Should a hyberbolic law indeed apply, high-temperature measurement would be effectually promoted.

METHOD OF MEASUREMENT.

29. *Consecutive adjustments.*—Thus far it has been my object to study the contraction of rock only. For this purpose the graduated faucet is turned on full and the furnace fired as far as 1,400° or 1,500°, when the first measurements are taken. With this end in view the length of the fusion tube is first accurately measured by the cathetometer observations at the bottom and the top. The telescope is then left adjusted for the top and the vertical micrometer (centrally adjusted) screwed down until its lowest point is just in contact with the cross hairs. After this the micrometer is further screwed down until the telephone registers a contact between the meniscus of the molten rock and the platinum micrometer tube. The difference of readings gives the depth of the meniscus below the top plane of the fusion tube. I usually repeated this measurement three times and then raised the micrometer screw again.

Thereupon the temperature measurements were made by connecting the terminals of the zero method consecutively with the upper, the middle, and the lower thermocouple.

Finally the cathetometer measurements of the length of the fusion tube and the micrometer measurement for depth of meniscus were again

[1] Am. Jour., Vol. XLII, pp. 134–135, 1891.

repeated, the latter three times. Properly uniform heating presupposed, it was permissible to regard the mean of the two sets of length measurements as coincident with the intermediate temperature measurement. This done, I usually waited ten or fifteen minutes to make another complete measurement under better conditions of constant temperature.

The graduated stopcock was then partially closed by a proper fractional amount, and after waiting fifteen minutes or more the same measuring operations were gone through with as before.

This I continued until the slag became sticky and solidification imminent, when longer waiting and greater slowness in changing the temperature is essential. Fortunately the observer can note the state of things very accurately; for when the point of solidification is approached a thread of the magma is drawn out of the fusion tube by the ascending micrometer tube until it breaks to form a rounded coating on the end of the tube. As temperature decreases, even by small amounts, the time that it takes to break and round off increases until finally this pulling out of a thread ceases and the enamel on the end of the micrometer tube does not change its form, being solid. It is at this point (1,095°) that the marked contraction of the molten mass in the tube occurs.

Having waited long enough for the lowest position of the meniscus, temperature may then be varied in larger steps again.

When the inside of the furnace has become dark, measurement is no longer possible. I then allowed the whole arrangement to cool over night, and the next morning determined both the depth of the solid meniscus by ordinary contact micrometric measurement, as well as by filling the top of the tube with water, and computing its bulk. This gives me my fiducial or normal volume.

To fill the fusion tube with rock at the outset of the work is a tedious operation. The material is added gradually in coarse grains, in proportion as the charge melts down, and after the tube is full some time must be allowed to insure the escape of air bubbles. Inasmuch as the fusion tube can at first be easily slipped out of its clay envelope, it is well to pack it as full of rock as possible before heating it.

30. Computation.—Let the linear expansion of the platinum fusion tube be given by $l=l_0\,(1+f(t)\,)$, where l and l_0 are the lengths at t degrees centigrade and at zero, respectively, and where $f(t)$ is a function of temperature. Let λ and λ_0 be the depths of the meniscus below the plane of the top of the fusion tube, and v and v_0 the volume of the inclosed molten magma, at t degrees centigrade and zero, respectively. Then if $(1+f(t)\,)^3$ is nearly enough equal to $1+3f(t)$; if the expansion constants of both platinum tubes be the same; and if in consideration of the small motion of the micrometer tube and the high temperature in the furnace, the air temperature above and outside of the furnace be nearly enough equal to zero, since $v_t/v_0=(l_0-\lambda)\,(1+f(t)\,)^3/(l_0-\lambda_0)$.

$$(1) \ldots\ldots\ldots (v_t-v_0)/v_0=3\,f(t)+(\lambda_0-\lambda)\,(1+3f(t)\,)/(l_0-\lambda_0).$$

Here $3f(t)$ is directly given after each observation as $(l_t - l_0)/l_0$, or it may be computed by some smoothing process from all the data as a whole.

The equation therefore gives the actual expansion of the rock in terms of unit of volume of solid rock at zero. If this be multiplied by the specific volume at zero, the absolute expansion is obtained.

An inspection of the equation shows that in the factor $\lambda_0 - \lambda$, the micrometer value of the lengths λ is to be inserted in both cases, supposing the contour of meniscus to remain similar to itself; whereas in $l_0 - \lambda_0$, the value of λ_0 determined from bulk measurements of the space at the top of the cold tube is suitable, since the tube is squared off below.

With this it is interesting to compare the results to be obtained in case of a float. If A be the height of the column of magma; h the submerged depth of the cylindrical float or bucket with flat base; and if $\delta A = A_t - A_0$, $\delta h = h_t - h_0$, $\delta v = v_t - v_0$, etc., for the temperatures t and t_0 respectively, then

$$(2) \ldots\ldots\ldots\ldots (3\,ft) + \frac{\delta H}{A-h} = \frac{\delta A - \delta h}{A_0 - h_0} + 3\frac{\delta l}{l_0} = \frac{\delta v}{v_0}$$

where δH is the rise of the float and l the length of the fusion tube. From this equation it appears at once that the float shortens the efficient length of the tube. Moreover, there is serious difficulty of properly determining A in this case. Hence, in view of the capillary and other errors encountered by a swimmer in a viscous liquid; the ease with which platinum at white heat welds with platinum vitiating the forms of both tube and swimmer; the tendency of air bubbles to accumulate around the latter and the probable utter failure of this method in indicating the passage from liquid to solid, induced me to prefer the other method. In case of a swimmer the observer does not surely know what he is measuring.

31. Errors.—First among these the lack of uniform temperature from the bottom to the top of the fusion tube may be mentioned. Moreover, only in the case of very slow changes of temperature is this quantity of like value from the axis to the circumference of the tube. I endeavored to meet these conditions. Moreover, since the temperature is actually measured at three points along a vertical, and the platinum tube is surrounded by the relatively nonconducting clay tube, I do not believe that serious discrepancy can here be apprehended. Specific inquiry will be made in the next paragraph in connection with the data obtained. Here I need only remark that it is unfortunate that the tube shows a tendency to be less hot at the top than at the bottom: for it is in the interest of thoroughly compact solidification that the tube cool from below upward. A column which cools first at the top is put into a state of dilitational strain after the manner of a Rupert drop, so that vacuities are left within the mass and the solidification contraction is obtained too small in value. I think a remedy for the difficulty in question will be found by feeding the upper burner from an independent gas supply.

Indeed I have frequently noted lateral funnel-shaped holes several millimeters in diameter and as much as 1 centimeter or more deep, terminating in the smooth surface of the meniscus. It is also possible that bubbles congregate under the surface of the molten magma, without breaking through it, giving rise to these cavities in the cold column. I have already stated that the ejection of gases on solidification is of very common occurrence.

At very high temperatures (say above 1,500°) I found the meniscus to gradually sink in depth even when temperature remained constant or rose in value, § 33. This may be due to the escape of bubbles in the thin liquid, or it may also be due to the fact that the tube is now insufficiently rigid to withstand the pressure of a column of molten rock 25 centimeters high. Examples will be given below, from which it appears that the meniscus, caet. par., does actually sink from day to day conformably with changes of length of the platinum tube. I suspect, therefore, that the clay tube which envelopes the fusion tube, besides acting favorably as a nonconductor, contributes to the high temperature rigidity of the system. After several heatings the platinum tube can no longer be removed trom the clay tube, into which it now fits tightly, without breaking the latter.

It has been assumed that the meniscus remains similar in form at all temperatures. This can only be partially true. The fused rock wets platinum so thoroughly, however, that convex forms of meniscus need never be apprehended. Indeed there is a tendency to flow or creep into crevices. After solidification, however, the meniscus is apt to be drawn down so as to be relatively deep near its center. Here is, therefore, an error which counteracts the tendency to dilitational strain. It is almost futile to make allowance for these discrepancies, but the micrometrically measured depth of the solid meniscus may be as much as ·2 centimeter or ·3 centimeter deeper than the mean surface computed from bulk.

Although too much reliance must, therefore, not be placed on the behavior of the solid state, yet the values are redeemed from the character of mere estimate, because the expansion of the platinum and its solid glass core are so nearly alike. This is a particularly fortunate chance, whereby the strains imposed on both the metal and the glass during cooling do not probably exceed the limits of elasticity of either. (§§ 33, 34 35.) From all of this it follows that the cooling of the furnace must take place so slowly as to give the viscous content of the fusion tube full time to adjust itself free from strain. Particularly are these precautions necessary near the solidifying point. In such a case experiment shows that the platinum tube is not dragged along appreciably by the solidifying magma, and the results retain a degree of trust worthiness much beyond what was to be anticipated, even in the solid state. At the same time dilitational strain is reduced to a minimum. In how far this has been accomplished satisfactorily can always be seen in the degree of uniform contraction of the platinum tube.

Another serious consideration is the allowance to be made for the expansion of the platinum probe *dd* of the vertical micrometer. The expansion as estimated above is too small, for it is not merely the amount by which the probe is lowered that is subject to expansion, but a considerable length of metal above the furnace passes from a lower to a higher temperature. Consecutive values for the depth of the meniscus will thus differ appreciably, the later ones being larger as a rule than the earlier ones. I hope, however, in the future to obtain an estimate of this discrepancy by measuring an amount of thrust through the sight tube with the cathetometer, and comparing this value with the corresponding value to be read off on the vertical micrometer. I have thought of making the micrometer screw hollow and providing it with an internal circulation of water; but this would be difficult to accomplish.

RESULTS.

32. *Arrangement of the tables.*—In the following tables l_0 and r_0 denote the length and radius of the cold platinum fusion tube, and λ'_0 the bulk value (water measurement) of the mean depth of the meniscus, the measurement being made on the day after the fusion experiments. The temperatures at the bottom, middle, and top of the fusion tube are given under θ_1, θ_2, θ_3, respectively, and θ is their mean value, observed at the time given. For each value of θ two data for the expansion of the rock, the volume expansion of the tube, and the actual expansion $\delta V/V_0$ of the rock are given, and they were obtained before and after the temperature measurement. Here $V\text{-}V_0$ is abbreviated δV and V_0 is the volume of the solid rock at zero. The data enclosed in parentheses show that in this case the value applied for the expansion of the tube is obtained as a mean result of all the measurements made. Otherwise the value directly observed was applied.

33. *Contraction of diabase. Tables.*—The results of my first series, being of inferior accuracy, will be omitted. Table 12 contains the results for the second series of experiments made on October 18, 1891. Here, too, the precaution of alternating volume measurements with the temperature measurements was not yet applied and the values given are less nearly coincident.

TABLE 12.—*Contraction of diabase. Second series.*

$l_0=25{\cdot}49^{cm}$; $\lambda_0={\cdot}86^{cm}$; $r_0={\cdot}75^{cm}$

θ_1 θ_2 θ_3	Mean. θ	Apparent volume expansion of the rock.	Volume expansion of the tube.	$\delta V/V_0$	Mean. $\delta V/V_0$	Time.	Remarks.
°*C*	°*C*					*Minutes.*	
1513	1514	·0442	.0411	....	·0853	0	Liquid. Viscous extension of tube?
1536	....	·0431	....	....	·0842	....	
1492	....	·0421	....	....	·0832	....	
1538	1544	·0379	·0399	....	·0778	25	Liquid.
1566	....	·0374	....	....	·0773	....	
1528	....	·0369	....	....	·0768	....	
1451	1480	·0345	·0378	....	·0721	50	Liquid.
1475	....	·0343	....	....	....	....	
1515	....	·0342	....	....	....	....	
1204	1202	·0302	·0300	....	·0602	75	Solidifying, chilled exteriorly.
1194	....	·0304	(·0290)	....	·0594	....	
1208	....	·0302	·0282	....	·0584	....	
896	872	·0074	·0201	....	·0275	100	Chilled solid.
864	....	·0050	(·0183)	....	·0233	....	
855	....	·0025	·0165	....	·0188	....	
804	770	·0016	·0141	....	·0157	130	Solid.
724	....	....	·0130	....	·0146	....	
783	....	....	·0120	....	·0138	....	
	20	·0000	·0000	....	·0000	Next day	Cold.

Taking each of the three values of $\delta V/V_0$ at 1514°, 1544°, 1480°, it is seen that the members of each set successively become more coincident. Moreover, the sweep downward and to the right of the means of the individual values of $\delta V/V_0$ is such as to indicate either that the tube sagged viscously or that the magma ejected bubbles or changed the figure of its meniscus. It seems to me that the platinum tube underwent stretching until it was finally restrained by the clay tube enveloping it. Rejecting the first datum, the mean volume expansion of the liquid is ·000050 per degree, a value which agrees very well with the subsequent work.

The passage from 1202° to 872° is abrupt, indicating that a melting point has been passed. Moreover, the wide divergence of the three data for $\delta V/V_0$ at 872°, shows that the cooling took place far too rapidly, so that the temperature of the rock must have been much higher than the thermocouples indicate. Finally the mean volume expansion of the solid magma below 872° is about ·000020 per degree, a value which also agrees very well with the work below.

If the solidifying point of the magma be 1095° (the value found in §§ 34, 35) then the contraction on solidifying may be estimated at 3 per cent. Thus it follows with certainty that diabase contracts on solidification and that its fusion behavior must be of a thoroughly normal type.

The amount of solidification contraction is, however, too small if too rapid cooling actually produces a strain of dilatation. For the same reason the values of $\delta V/V_0$ for the liquid state, though correct in their relations to each other, must be uniformly too small, for the factor V_0 used is too large. All this is proved directly by the next two tables, but it may be inferred here from the contraction curve of the platinum tube. This shows reasonable uniformity of contraction as far as 900°, after which, however, there is a break to much smaller rates of contraction, showing I think that the platinum *tube has been dragged* along by the too rapidly solidifying magma.

34. Contraction of diabase. Tables and chart.—The data of my third series of experiments, made on October 20, 1891, are given in table 13. The precautions for slow cooling were fully taken, and the solidification point is now sharply apparent.

TABLE 13.—*Contraction of diabase. Third series.*

$l_0 = 25{\cdot}466^{cm}$; $\lambda_0 = 1{\cdot}424^{cm}$; $r_0 = {\cdot}75^{cm}$.

θ_1 θ_2 θ_3	Mean. θ	Apparent volume expansion of rock.	Volume expansion of the tube.	$\delta V_1/V_0$ $\delta V_2/V_0$	Mean. $\delta V/V_0$	Time.	Remarks.
°*C.*	°*C.*					*Minutes.*	
1360	1386	·0452	·0358	·0810	·0811	0	Liquid.
1396		·0454	(·0356)	·0812	(·0809)		
1403				(·0808)			
				(·0810)			
1286	1300	·0‧37	·0340	·0777	·0778	23	Liquid.
1304		·0438	(·0334)	·0778	(·0772)		
1311				(·0771)			
				(·0772)			
1163	1166	·0406	·0297	·0703	·0704	53	Sticky.
1167		·0409	(·0300)	·0706	(·0707)		
1168				(·0706)			
				(·0709)			
1097	1093	·0376	·0270	·0646	·0646	86	Very sticky.
1093		·0333	(·0281)	·0603			To be drawn out in threads.
1089				(·0657)	(·0657)		Solidifying gradually.
				(.0614)			
1102	1095	·0014	·0273	.0288	·0287	111	Solid.
1095		·0013	(·0282)	.0286	(·0296)		
1088				(.0296)			
				(.0295)			
929	896	·0000	·0211	.0211	·0212	157	Solid.
897		·0002		.0213			
863							
461	468	—·0004	·0081	·0077	·0079	185	Solid.
433		± ·0000		·0081			
510							
	20	·0000	·0000	·0000	·0000	Next day.	Cold.

Rock, mean actual expansion, solid, 0° — 1000°, ·0000250.
Rock, mean actual expansion, liquid, 1100° — 1500°, ·0000470.
Rock, expansion on fusion (1095°), ·0390.
Rock, mean apparent expansion, solid, 0° — 1000°, ·0000007.
Rock, mean apparent expansion, liquid, 1100° — 1500°, ·0000205.
Tube, mean expansion below 1000°, ·0000240.
Tube, mean expansion above 1100°, ·0000265.

These values are fully represented in the chart, Plate V, where the actual expansion is given by the heavy curve *dcbef*, the ordinates being the volume increments and the abscissæ temperatures. The apparent expansion of the rock is shown by the light curve *lk gh*, the ordinates of the solid contour *lk* being nearly zero, so that the tube and contents expand nearly at the same rate, whereas the liquid contour *gh* follows with a marked jump and shows great uniformity. Finally the expansion of the platinum tube is represented by the dotted curve *dc a i*. The exceedingly small break at *a*, which indicates the amount of drag or shortening of the length of the platinum tube by the solidifying rock, shows how well the operation of cooling has here been conducted, and proves the results to be trustworthy throughout.

One of the important results obtained from the chart is the occurrence of a sharply-defined solidifying point at 1093°. Here, therefore, is a method by which this point of the rock can be defined free from non-intrinsic tests.

Finally, it may be noted that so long as the magma is liquid, the distribution of temperature along the fusion tube is fairly constant, and and is usually hotter at the top. After this the discrepancy increases, probably from lack of convective conduction of the solid magma.

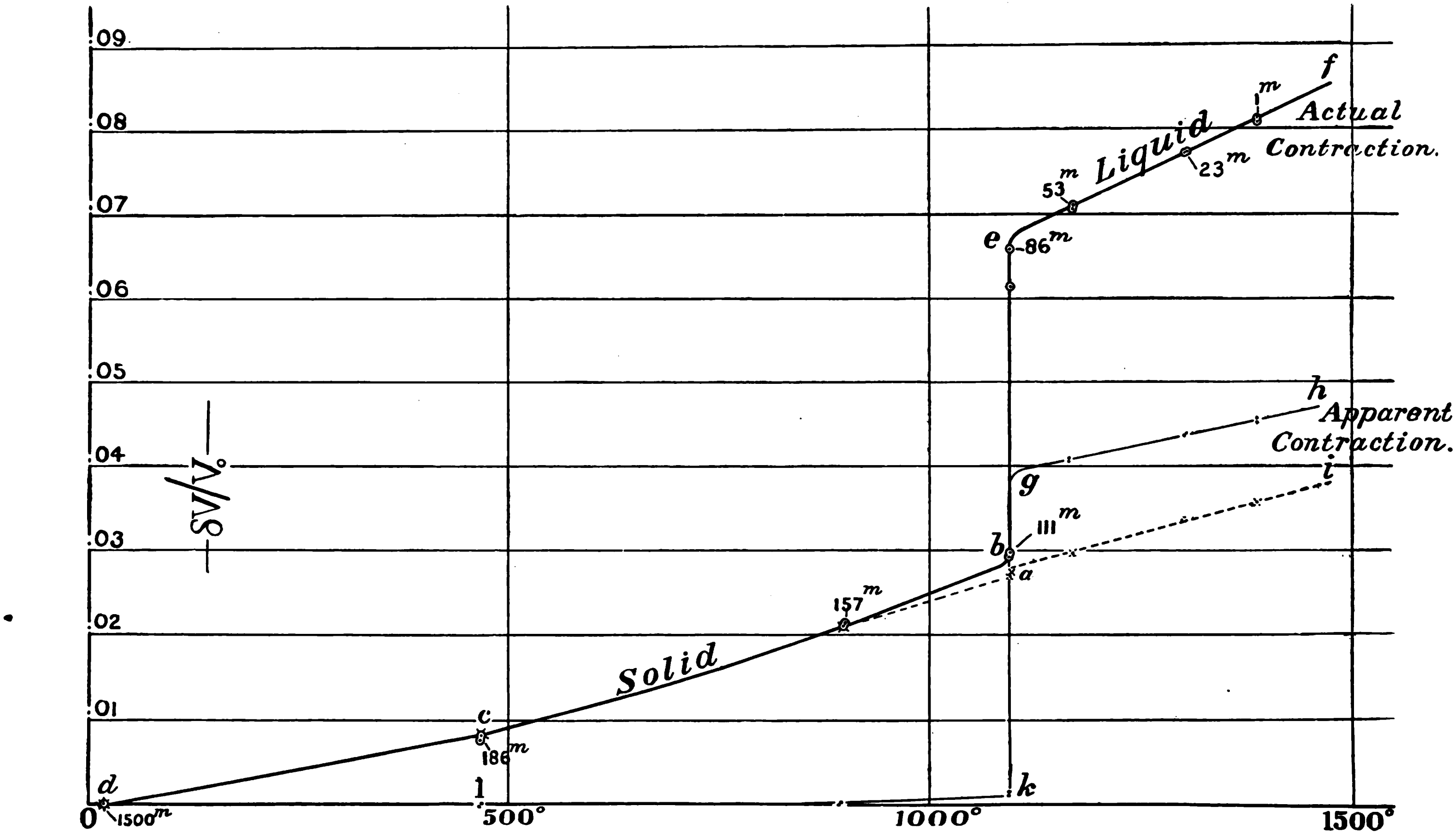
35. *Contraction of diabase. Tables and chart.*—The data of my last series of experiments, made on October 21, 1891, with all precautions necessary, are given in Table 14. Two complete sets of result for each step of temperature are given.

TABLE 14.—*Contraction of diabase. Fourth series.*

$l_0 = 25.447^{cm}$; $\lambda'_0 = 1.220^{cm}$; $r_0 = .75^{cm}$

θ_1 θ_2 θ_3	Mean. θ	Apparent volume expansion of rock.	Volume expansion of the tube.	$\delta V_1 / V_0$ $\delta V_2 / V_0$	Mean. $\delta V / V_0$	Time.	Remarks.
C°.	°C.	—	—	—	—	*Minutes.*	
1374	1388	·0403	·0357	·0760	·0760	5	Liquid.
1394		·0404	(·0356)	·0761	(·0760)		
1395				(·0759)			
				(·0760)			
1415	1421	·0407	·0362	·0768	·0770	20	Liquid.
1431		·0409	(·0364)	·0771	(·0771)		
1417				(·0771)			
				(·0773)			
1318	1319	·0394	·0341	·0734	·0731	50	Liquid.
1324		·0387	(·0339)	·0727	(·0730)		
1315				(·0733)			
				(·0726)			
1304	1305	·0383	·0350	·0733	·0736	65	Liquid.
1308		·0390	(·0335)	·0740	(·0721)		
1304				(·0718)			
				(·0725)			
1204	1190	·0357	·0316	·0673	·0672	90	Sticky.
1189		·0355	(·0305)	·0671	(·0661)		
1176				(·0662)			
				(·0660)			
1177	1163	·0355	·0299	·0655	·0652	105	Very sticky. To be drawn out in threads.
1158		·0349	(·0299)	·0649	(·0652)		
1153				(·0655)			
				(·0649)			
1138	1112	·0339	·0286	·0625	·0628	128	Top encrusted.
1109		·0344	(·0286)	·0630	(·0628)		
1090				(·0625)			
				(·0630)			
1117	1092	·0200	·0275	·0475	·0475	151	Solidifying.
1088		·0155	(·0280)	·0430	(·0480)		
1072		·0091		·0366			
				(·0480)			
				(·0435)			
				(·0371)			
1109	1092	·0032	·0282	·0315	·0287	175	Solidifying.
1081		·0005	(·0280)	·0287	(·0285)		
1086				(·0313)			
				(·0285)			
946	914	·0013	·0213	·0226	·0223	198	Solid.
903		·0006		220			
893							
900	855	·0003	·0199	·0202	·0202	210	Solid.
827		·0003		202			
837							
20		·0000	·0000	·0000	·0000	Next day.	Cold.

Rock, mean actual expansion, solid, 0°—1000°, ·0000250.
Rock, mean actual expansion, liquid, 1100°—1500°, ·0000468.
Rock, mean apparent expansion, solid, 0°—1000°, ·0000005.
Rock, mean apparent expansion, liquid, 1100°—1500°, ·0000218.
Tube, mean expansion below 1000°, ·0000235.
Tube, mean expansion above 1100°, ·0000260.
Rock, expansion on fusion, (1093°), .0340.



CONTRACTION OF MOLTEN DIABASE, CONTINUOUSLY FROM LIQUID TO SOLID.

These data are given in the chart, Pl. VI, Fig. 1, on the same plan as in the preceding case. The inferences to be derived are identical with those of the preceding paragraph. The sudden contraction of the rock on solidifying is of smaller value here, but this is to some extent compensated by the greater longitudinal compression of the fusion tube, as shown at *a* in the curve *c a i*. It is interesting to note that in both series 3 and 4 the first length measurement of the tube at the solidifying point of its contents, is smaller than the second, showing the end thrust to have diminished in value, while the tube has recuperated from its strain. It is also well to note that the sag of tube, as expressed in the cold lengths 25·49 centimeters in the second series, 25·47 centimeters in the third series, and 25·45 centimeters in the fourth series is small, but quite appreciable.

Regarding the differences of λ_0 (micrometric), and λ'_0 (bulk measurement), which is ·34 centimeter in the fourth series, ·13 centimeter in the third series, and ·38 centimeter in the second series, the remarks made in § 31 apply. Hence the third series is the one in which cooling was slowest, and in this the solidification contraction is largest. Lateral fissures opening into the solid meniscus were present in both these cases. Regarding the depth λ, of the solid meniscus at the outset, and at about the same temperature, 1387°, I found $\lambda =$ ·50 centimeter in the third series, and $\lambda =$ ·62 centimeter in the fourth series, showing enlargement of the volume of the fusion tube.

Finally, as before, temperatures are hotter at the top or fairly uniform so long as the magma within the fusion tube is very liquid. Near the solidifying point, however, and thereafter, the top is colder. For this reason, since solidification commenced at the top, the data of this paragraph show a smaller solidification contraction than in the last instance.

36. *General remarks.*—The charts show how important it is to measure the expansion of the fusion tube, which, if neglected, would distort the liquid expansion fully 50 per cent. Moreover I have no doubt that when fusion is made in clay crucibles which are apt to become friable after heating, the clay on cooling is quite at the mercy of the more tenacious slag within, and changes its volume accordingly.

Again even in case of slow cooling solid contraction tends to express itself as a dilatational strain, and if gas bubbles are ejected by rocks on solidifying solid volumes will be found too large and the solid contractions, etc., too small. Hence I place greatest reliance in the solidification contraction given in the third series, the value being 3·9 per cent.

Naturally, I also made special experiments on the floating of solid rocks on the molten magma, cf. § 20. To my surprise such flotation always occurs, notwithstanding the fact that originally the cold rock must be 8 per cent + 10 per cent more dense than the molten rock, since it is both solid and cold as well as possessed of organized rock structure. It soon appeared, however, that the cause of such flotation is crudely mechanical, since the rock in virtue of its weight simultaneously hollows out a cavity and chills it, thus forming a little solid boat in which it floats on the very viscous slag below. This is shown in Plate VI, Fig. 2, where *a* is the body of rock, *AA* the molten magma, and *bb* the solidified bowl-shaped skin. It may be observed that flotation is assisted by viscous friction of the blanket *bb* on the magma *AA* which supports the blanket and keeps it distended. I then attempted to make Niess and Winkelmann's "Fundamental-versuch" by submerging the rock; but here both on account of the intense white glare of the furnace and the tendency to chill at the surface of the magma during the operation I was not able to reach any definite point of view.

Results for thymol are given in Plate VI, Fig. 3, for comparison. §38.

37. Fusion and solidification alternating.—To corroborate the above work, I made some experiments by measuring the expansion on fusion, as well as the contraction on solidification. These are contained in Table 15, where the notation is the same as above. The zero lengths (l_0, λ_0, etc.), were taken from the above work, as was also the expansion of platinum.

TABLE 15.—*Fusion and solidification alternating.*

Time.	θ_1 θ_2 θ_3	Mean θ	$(\delta v/v_0)$ $\times 10^4$	Time.	θ_1 θ_2 θ_3	Mean θ	$(\delta v/v_0)$ $\times 10^4$
Minutes.	°	°		*Minutes.*	°	°	
20	1139	1158	332	195	1059	1086	302
	1163		343		1086		300
	1173				1113		
45	1235	1239	511	225	1097	1067	274
	1246		614		1066		271
	1234				1039		
70	1254	1265	664	240	1167	1183	338
	1275		671		1190		373
	1266				1192		
95	1285	1286	678	260	1239	1239	538
	1294		681		1246		595
	1280				1232		
127	1157	1174	604	280	1087	1113	328
	1176		591		1115		302
	1188				1138		
165	1146	1134	425				
	1125		404				
	1132						

The difficulty with these experiments lies in the insufficient time allowed for fusion and solidification (§§33–37). In the former case irregularities are unavoidable, since it is impossible to heat a solid rod of rock uniformly throughout its length. The high solidifying point, here, probably follows from the fact that the fusion was not complete. This is seen in Fig. 3, where the individual data are marked by numerals indicating the time at which the observation was made, and where the first cycle is indicated by a heavy line, the second by a light line. I suspect, therefore, that in rocks melting and solidifying points are different and may be 100° apart. Hence the large contraction at a definite degree of temperature observed above, was due to very slow cooling of an undercooled mass.

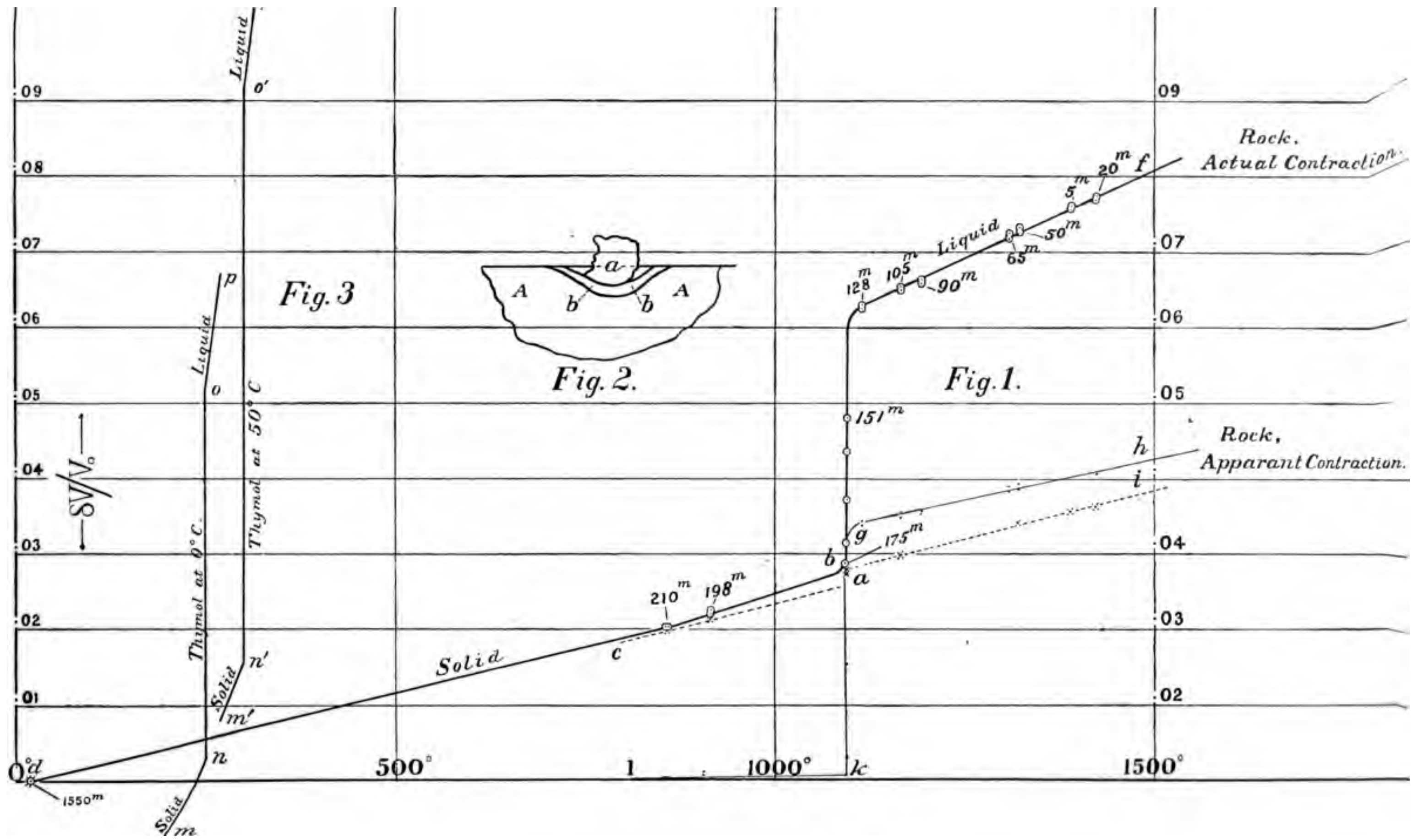


Fig. 3
Fig. 2.
Fig. 1.
δV/V₀
Thymol at 0° C.
Thymol at 50° C
Liquid
Solid
Rock,
Actual Contraction.
Rock,
Apparent Contraction.
500°
1000°
1500°
1550m
210m
198m
175m
151m
128m
105m
90m
65m
50m
5m
20m

The amount of volume contraction agrees in both cases with the above data, and this is the chief point at issue.

INFERENCES.

38. Comparison with thymol.—Since the fusion of rocks like diabase is thus thoroughly normal, it follows that melting point must increase with pressure. It is well to examine tentatively into the nature of this relation, and for this purpose I have drawn certain unpublished results of mine for thymol, on the same scale used for the rock. In Pl. VI, Fig. 3, *m′n′o′p′* shows the contraction of thymol at its melting point, where the substance is liquid along *o′p′* and solid along *m′n′*. Similarly, *mnop* shows the contraction of thymol at 0°C. These results indicate that

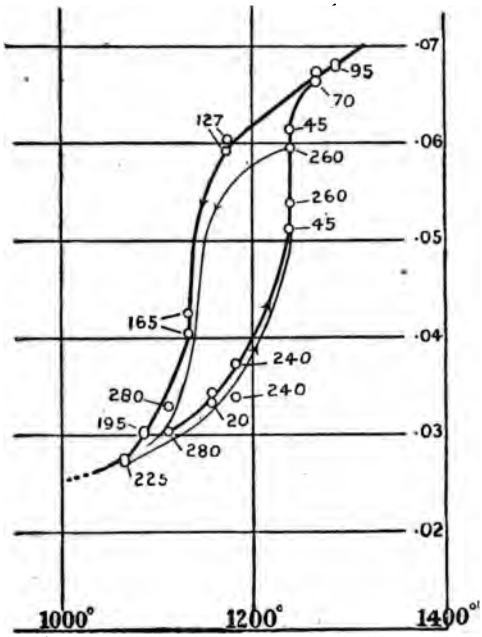


FIG. 3.—Cyclic volume changes produced by alternate fusion and solidification of rock magma (diabase).

the solidification contraction decreases in proportion as the thermal expansion ($[\delta(V/V_0)/d\theta]_\theta$ where θ denotes temperature) decreases. The solidification contraction of thymol, therefore, like its coefficients of expansion, is larger than the similar variable in the case of rock. The relations are such that if liquid thymol could be cooled down to $-25°$ it would then show the same solidification contraction as the silicate.

39. Lower critical temperature.—Analogously the compressibility of the rock will show decidedly larger values than in organic bodies; and hence it also follows that whereas the lower critical pressure liquid-solid of naphthalene, for instance, should, according to my experiments, lie somewhere in the region of 10,000 atmospheres, the corresponding pressure in the case of rock magma must be indefinitely higher. In other words, the consecutive isopiestics of the magma must lie very much nearer together than the corresponding isopiestics of naphthalene, supposing the pressure to vary in like steps in both cases.

40. Melting point and pressure.—From this, however, it does not by any means follow that the relation of melting point to pressure will be different in the silicate and in the carbon compound. In the latter case, data for normal fusions are available in case of wax, paraffin, spermaceti, and naphthalene, and for these dT/dp, the relation of melting point to pressure, lies within the narrow margin of ·020 to ·036, data moreover which even for the same substance[1] are subject to variation. Thus I found that in naphthalene dT/dp varied from ·027 to ·035, according as melting points or solidifying points were suitably considered. Since, therefore, the fusion both of the organic bodies and the silicate is alike in character, it is probable that the same factor dT/dp will correspond to both cases. The direct consideration of these questions will be the subject of the next chapter.

[1] See my work on naphthalene, Am. Journal Sci., vol. 42, 1891, p. 144 et seq.

CHAPTER III.

THE THERMAL CAPACITY OF IGNEOUS ROCK, CONSIDERED IN ITS BEARING ON THE RELATION OF MELTING POINT TO PRESSURE.[1]

PRELIMINARY REMARKS.

41. Introductory.—The present experiments are in series with the volume measurements of my last chapter, and the same typical diabase, § 18, was operated upon. Since it is my chief purpose to study the fusion behavior of silicates, more particulurly the relation of melting point to pressure, the observations (700° to 1400°) are restricted to an interval of a few hundred degrees on both sides of the region of fusion. The solid locus found, however, is one which would be nicely tangent to an initial specific heat of about ·2, the value which probably obtains. The liquid locus is again indicative of a transitional temperature.[2]

42. Literature.—Experiments similar to the present, but made with basalt, were published quite recently by Profs. Roberts-Austen and Rücker.[3] In view of the normal behavior occurring throughout my own data, the irregularities obtained by these gentlemen in case of different methods of treatment (heating in an oxidizing or reducing atmosphere, repeated heating, sudden cooling, etc.), the anomalously large specific heat between 750° and 880°, where basalt is certainly solid, and the absence of true evidences for latent heat[4] make their results somewhat startling. Basalt is lithologically so near akin to diabase that one would anticipate a close physical similarity in the two cases. Unfortunately, the account given of the work with basalt is meager, and detailed comparisons are therefore impossible. I will only state that as nobody had then compared the platinum-rhodium couple with the air thermometer, I should not have regarded a standardization by means of a single melting point sufficient.

[1] Cf. Am. Journal Sci., vol. 43, 1892, pp. 56, 57.

[2] Am. Journal Sci., vol. 42, 1891, p. 145.

[3] Roberts-Austen and Rücker: Phil. Mag., vol. 32, 1891, p. 355.

[4] Supposing basalt to melt below 1200°. The authors state that the specific heat of basalt is greater in the liquid than in the solid state, but no remarks are made as to whether the rock was fused at their higher temperatures or not.

APPARATUS.

43. The rock to be tested.—About 30 grams of diabase were fused in a small platinum crucible, together with which they were to be dropped into the calorimeter. Two of these charged crucibles were in hand and used alternately. After removing the (cold) crucible from the water into which it had been dropped at red or white heat, the surface of the glass usually shows a smooth unfissured gloss. This, however, is only apparent, for after drying and weighing, the mass is often found to have increased in weight fully 5 per cent. I was at first inclined to believe that this was due to water chemically absorbed by the viscous magma; but the water is only mechanically retained, for it passes off completely after twenty-four hours' exposure to the atmosphere, or by drying at 200° for, say, 30 minutes. Hence, at the beginning of each measurement I weighed the crucibles again, having thoroughly dried them at 200°. The solid glass dropped into water at low red heat soon shows a rough and fissured surface, and changes in color from black to brown, possibly from the oxidation of the protosilicate to the sesquisilicate of iron. The effect of this change (if it be a chemical change and not a mere change of the optical character of the surface) is inappreciable, at least by the following calorimetric method.

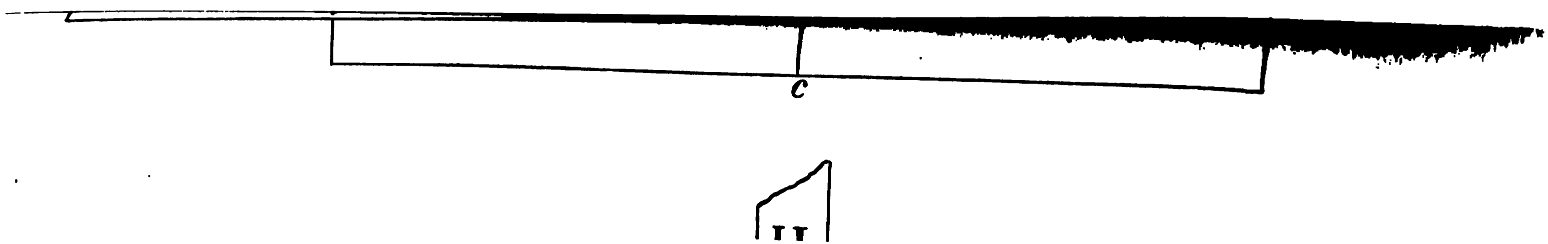
Throughout the course of the work the charge was neither changed nor replenished.

44. Thermal capacity of platinum.—Since the charge of molten rock and the crucible are submerged together, it is necessary to know the heat given out by the known weight of the platinum. Data for this purpose have been published by Violle.[1] In these the high temperature specific heat at $t°$ is given as $\cdot 0317 + \cdot 000012t$, whence the increase of thermal capacity from zero to the same temperature is $(\cdot 0317 + \cdot 000006t)\, t$. This is the allowance I made per gram of platinum crucible.

45. Furnace.—Inasmuch as heat is rapidly lost by radiation from the white hot slag, it is necessary to transfer the crucible from the furnace into the water swiftly. Trap-door and false-bottom arrangements, which at first suggested themselves, were discarded, because the mechanism clogs the furnace, interferes with constancy of temperature, and is too liable to get out of order.

The furnace adopted is shown in Pl. VII, Figs. 1 and 2, in sectional elevation and plan. The body consists of two similar but independent half cylinders *AA* and *BB* of fire clay, properly jacketed and closed below, which come apart along the vertical plane *cccc*. The lid *LL*, however, is a single piece, fixed in position by an adjustable arm (not shown). Each of the halves of the body of the furnace is protected by a thick coating of asbestos *CC*, *DD*, and by a rigid case of thick sheet iron, *EE*, *FF;* clamp screws *g*, *g*, *g*, *g*, pass through this in such a way as

[1] Violle: C.R., vol. 85 1877, p. 543; vol. 87, 1878, p. 981; vol. 89, p. 702, 1879; Phil. Mag., (5), IV, p. 318, 1877.


c

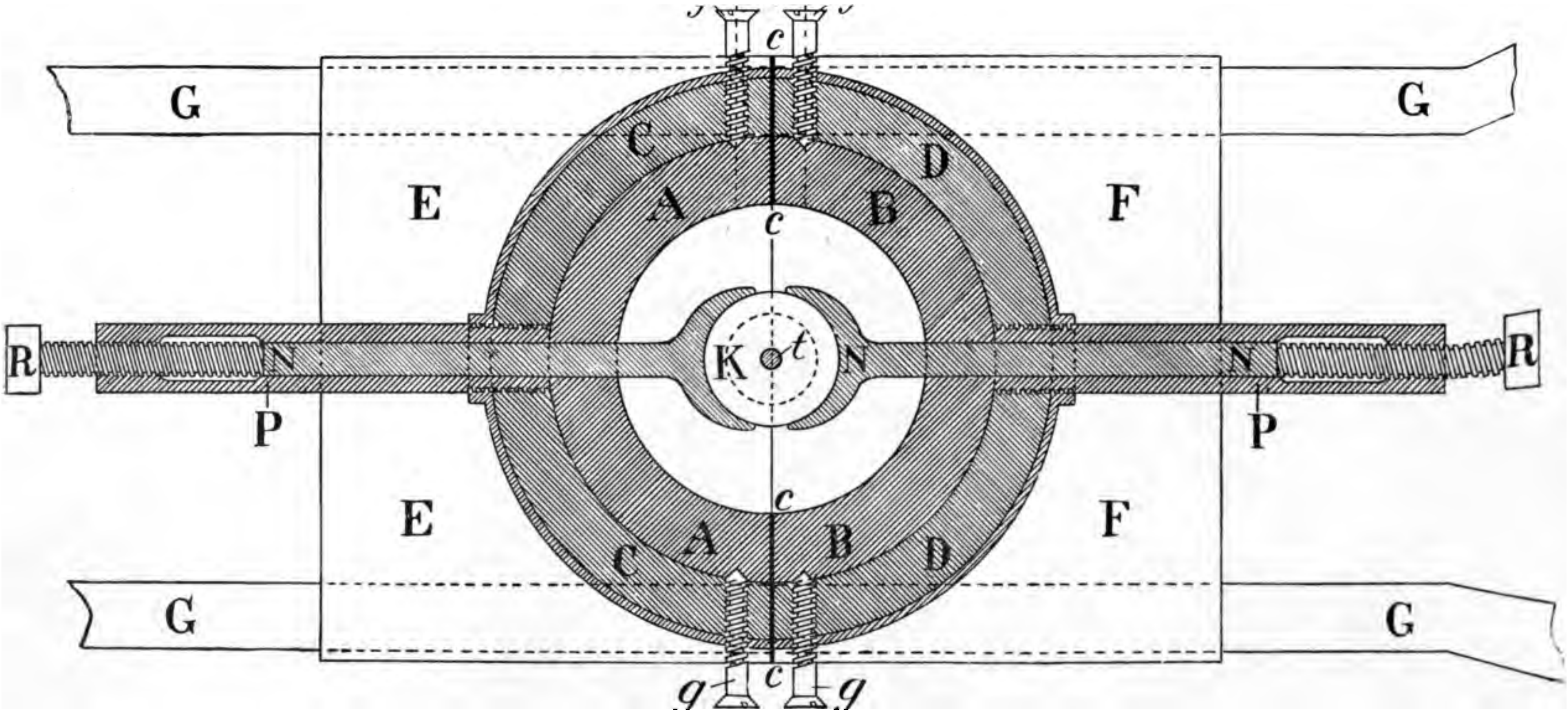


Fig. 2.

FURNACE FOR CALORIMETRY, WITH THE BODY K (CRUCIBLE), THE PYROMETER *tt*, AND THE HOLDERS N N IN PLACE. SCALE ⅛.

to hold the fire clay and asbestos firmly in place. The horizontal base of the casing *E*, *F*, is bent partially around the two iron slides *G*, *G*, along which the two halves of the furnace may therefore be moved at pleasure while the lid *L* is stationary, as is also the blast burner *H*, clamped on the outside and entering the furnace through a hole left for that purpose.

The charged crucible is shown at *K*, and is held in position by two crutch-shaped radial arms, *N*, *N*, of fire clay, the cylindrical shafts of which fit the iron tubes *P*, *P* snugly and are actuated by two set screws, *R*, *R*. The two tubes *P*, *P*, moreover, are covered with a nonconductor, and thus subserve the purposes of handles, by grasping which the two halves of the furnace may be rapidly jerked apart. It is by this means that the crucible is suddenly dropped out of the furnace into the calorimeter below. Care must be taken to have the arms free from slag, as otherwise the crucible is not at once released.

46. Temperature.—As in a former case, the temperature of the furnace is regulated at pleasure by forcing the same quantity of air through it at all times, but lading this air with more or less gas supplied by a graduated stop cock. The amount of gas necessary in any case is determined by trial, and observations are only to be taken after fifteen or twenty minutes' waiting, when the distribution of temperature is found to be nearly stationary. It would have been better to have curved the bottom of the furnace cylindrically, so as to surround the crucible with a whorl of flame. The temperature of the crucible is never quite constant from point to point. I therefore measured this datum at three points, near the bottom, middle, and top of the charge. For this purpose the fire clay insulator *t t* of the platinum platinum-iridium thermocouple *ab* passing through a hole in the lid is adjustable along the vertical. Before dropping the crucible the thermocouple is withdrawn from the charge and suspended above it. The cold junction communicates with the terminals of the zero method submerged in a bath of petroleum and provided with a thermometer.

When the charge is solid, a small platinum tube which has been previously sunk into the molten glass before solidification (see Pl. VII, Fig. 3), enables the observer to make the three temperature measurements, as before. In later measurements I also incased the insulator of the thermocouple in a platinum tube, closed below (see Pl. VII, Fig. 1), when making the temperature measurements for the molten charge. Slag at high temperature being a good conductor, it is not impossible that hydro-electromotive forces may enter, slightly distorting the thermoelectric data.

When constancy of temperature is being approached the hole in the lid *L L* is closed with asbestos, and the products of combustion escape by the seam in the side. This facilitates manipulation above the furnace. The crucible is visible in part through the seam in question.

47. *Calorimeter.*—This was a vessel of thin *tinned sheet iron*, *28 centimeters* long and 8 centimeters in diameter, having a water value of 19 g. cal. and holding a charge of about 1,200 grams of water. The inside of the calorimeter was provided with a helical strip running nearly from top to bottom. The vessel, contained within a suitable environment, was supported on a hard rubber stem, which could be grasped below, and served as an axle around which the calorimeter could be rotated from without. In this way the water within was churned. Three small, hard-rubber rowels near the top gave steadiness to the motion. They were fixed to the hollow cylindrical vessel (environment) provided with a hollow hinged lid, through both of which a current of cold water, at constant temperature, continually circulated. Thus the temperature surrounding the calorimeter was at all times given, and the correction for cooling could be found and applied with accuracy. I pass by the description of this apparatus rapidly here, inasmuch as I shall recur to it in connection with other calorimetric work. The box of the calorimeter with its projecting stem was movable on a small tramway, the tracks of which lay at right angles to the slides *G G*. (Pl. VII, Figs. 1 and 2.) Thus when the measurements showed a sufficiently constant temperature in the furnace, the lid of the box was opened and the calorimeter rolled directly under the furnace. After receiving the crucible, the calorimeter was again rolled away and the lid of the box closed, whereupon the temperature measurements were made by aid of a sensitive thermometer inserted through a hole in the lid.

I may add here that should I have occasion to extend the work to other substances, I would have a bullet-shaped platinum crucible provided with a central tube similar to Fig. 3, made at the outset. In this way splashing during the drop of the crucible into water would be to a great extent obviated.

RESULTS.

48. *Method of work.*—While waiting for the temperature of the furnace to become stationary, I made the initial measurements for the cooling of the calorimeter, in time series. Knowing, therefore, the time at which the body was dropped, I also knew accurately the temperature of the water into which it was dropped. Just before this the three measurements for temperature of the charge had also been made in time series. The experiments showed that ten minutes after submergence, the crucible and charge might be safely considered cold, for the minimum temperature of the calorimeter was reached after about five minutes. Hence the time from 10 minutes to 15 minutes after submerging could be utilized for making the final measurements for cooling. Knowing these, I interpolated the rates of cooling for any intermediate times.

Thus while the calorimeter was being constantly stirred, its temperature was measured at the end of every minute. Hence I knew the mean excess of its temperature above that of *its environment during* the course of every minute, and was able to add the corresponding allowance for radiation at once. How important this is the tables below will fully show. It may amount to 10 per cent of the total temperature increment. The only drawback against obtaining sharp values for the consecutive rates of cooling is to be found in the lag error of the thermometer; but this is eliminated in a long series.

The calorimeter was always weighed before and after the work, but the latter datum was taken. Similarly, as has been stated, the crucible was weighed before and after heating and the latter datum taken. Some charge is always removed or added by the thermocouple.

49. Arrangement of the tables.—There being two crucibles and two tubes (Pl. VII, Fig. 3), they are distinguished by *I* and *II*. In all cases τ is the temperature of the environment, m the mass of the charge, M the water value of the calorimeter (corrected for temperature). Θ is the temperature at the bottom, middle, and top of the charge at the time of submergence, for which a mean value is also given. The temperature observed in the calorimeter at the time specified is given under θ, and a parallel column shows the correction of θ for radiation. Finally, the computed thermal capacity of the platinum crucible and appurtenances (correction h), and the thermal capacity h of the charge given for each of the consecutive times, are found in the last columns. A few obvious remarks follow. All data are referred to gram calories.

50. Tables.—In the data of the first series (Table 16) only one value of Θ occurs for the liquid state. Moreover, the construction of the furnace was somewhat faulty, not being flat-bottomed. Hence these results are of inferior accuracy, and their chief purpose is to bear out the results of Table 17, which are the best I could obtain.

TABLE 16.—*Thermal capacity of diabase. First series.*

Platinum crucible *I*, 11·169 g; platinum tube *I*, ·985 g.
Platinum crucible *II*, 11·271 g; platinum tube *II*, ·654 g.

No.	τ	Time.	Θ	Mean Θ M m.	θ	Correction θ	correction h.	h.	Remarks.
	°C	minutes.			°C		g. cal.	g. cal.	
I	16	25	....	1306°	25·90	....	....	....	Immersion
		26	....	1145 g	34·90	·07	16·6	291	Liquid.
		27	....	33·75 g	36·30	·17	....	342	
		28	....	....	36·60	·27	....	355	
		30	....	....	36·59	·48	....	363	}
		33	....	....	36·32	·79	....	364	} 364
		36	....	....	36·04	1·10	....	365	}
I	12	5	....	1367°	14·92	....	....	....	Immersion
		6	....	1202 g	22·80	·02	17·9	267	Liquid.
		7	....	33·36 g	25·20	·06	....	355	
		8	....	....	25·50	·11	....	367	
		10	....	....	25·58	·20	....	372	
		13	....	....	25·40	·33	....	370	}
		16	....	....	25·25	·46	....	370	} 370
		19	....	....	25·12	·60	....	370	}
II	12	26	....	1378°	22·16	....	....	....	Immersion
		27	....	1202 g	30·00	·05	20·7	302	Liquid.
		28	....	29·32 g	31·00	·13	....	346	
		29	....	....	31·70	·21	....	378	
		31	....	....	31·67	·38	....	384	
		34	....	....	31·42	·63	....	384	}
		37	....	....	31·21	·87	....	385	} 385
		40	....	....	30·97	1·11	....	386	}

TABLE 16.—*Thermal capacity of diabase. First series*—Continued.

No	τ	Time.	Θ	Mean Θ M m.	θ	Correction θ	correction h.	h.	
	°C	minutes.			°C		g. cal.	g. cal.	
I	12	36		1337°	14·55				Immers
		37		1196g	22·40	·02	18·0	275	Liquid.
		38		32·22g	24·00	·07		337	
		39			24·80	·12		368	
		41			24·79	·23		371	
		44			24·68	·39		373	
		47			24·55	·54		375	373
		50			24·40	·69		375	
II	12	9		1274°	21·92				Immers
		10		1196g	28·50	·05	17·1	256	Liquid.
		11		29·16g	29·80	·13		312	
		12			30·60	·21		349	
		14			30·63	·38		356	
		17			30·42	·62		358	
		20			30·22	·86		359	358
		23			29·98	1·10		359	
I	12	15	1199	1166°	14·87				Immers
		16	1163	1195g	22·60	·03	16·7	271	Solid.
		17	1138	32·22g	23·10	·09		292	
		18			23·30	·15		302	
		20			23·37	·27		308	
		23			23·21	·45		309	
		26			23·15	·63		314	311
		29			22·98	·81		314	
II	12	1	1100	1078°	21·16				Immers
		2	1074	1196g	27·20	·04	16·4	232	Solid.
		3	1060	29·16g	27·80	·09		259	
		4			27·90	·15		266	
		6			27·76	·25		264	
		9			27·59	·42		264	
		12			27·41	·58		263	263
		15			27·25	·74		263	
I	11	1	1021	1001°	14·89				Immers
		2	998	1196g	20·40	·02	13·9	191	Solid.
		3	983	32.23g	21·40	·07		230	
		4			21·58	·11		238	
		6			21·58	·20		242	
		9			21·45	·34		242	242
		12			21·31	·47		242	
II	11	2	1035	1025°	19·76				Immers
		3	1025	1195g	25·00	·03	15·5	201	Solid.
		4	1015	29·16g	25·90	·08		240	
		5			26·20	·14		254	
		7			26·10	·25		255	
		10			25·90	·41		253	
		13			25·72	·57		252	253
		16			25·55	·73		252	
I	11	1	889	880°	16·19				Immers
		2	880	1198g	21·80	·03	12·0	198	Solid.
		3	872	32·24g	21·90	·06		203	
		4			21·94	·10		206	
		6			21·83	·18		204	
		9			21·70	·30		204	204
		12			21·59	·41		204	
II	11	8	827	829°	20·07				Immers
		9	827	1192g	24·50	·04	12·1	171	Solid.
		10	833	29·16g	24·90	·09		189	
		11			24·90	·14		191	
		13			24·85	·23		193	
		16			24·67	·37		191	
		19			24·51	·51		190	191
		22			24·39	·65		190	

Table 17.—*Thermal capacity of diabase. Second series.*

Platinum crucible *I*, 11·169g; Platinum tube *I*, ·985g.
Platinum crucible *II*, 11·271g; Platinum tube *II*, ·654g.

No.	τ	Θ	Mean Θ M m.	Time.	θ	Correction θ	Correction h.	h.	
	°C.	°C.		minutes.	°C.	°C.	g. cal.	g. cal.	
II	12	1265	1251°	4	18·94	....	....	....	Immersion
		1246	1189 g	5	24·60	·04	20·6	236	Liquid.
		1241	26·39 g	6	26·05	·10	....	305	
				7	26·52	·16	....	329	
				9	26·61	·30	....	339	
				12	26·45	·50	....	341	
				15	26·25	·69	....	340	340·5
				18	26·08	·88	....	341	
I	12	997	993°	2	14·07	....	....	....	Immersion
		995	1192 g	3	20·20	·01	13·8	213	Solid.
		987	32·22 g	4	20·56	·03	....	227	
				5	20·80	·05	....	237	
				7	20·80	·10	....	239	
				10	20·75	·16	....	239	238·3
				13	20·61	·22	....	237	
II	12	1260	1251°	3	19·34	....	....	....	Immersion
		1251	1190 g	4	26·00	·04	20·8	285	Liquid.
		1243	26·07 g	5	27·00	·10	....	333	
				6	27·20	·16	....	345	
				8	27·03	·27	....	342	
				11	26·86	·45	....	343	
				14	26·69	·62	....	343	342·5
				17	26·49	·80	....	342	
II	10	1354	1334°	5	13·78	....	....	....	Immersion
		1333	1190 g	6	20·60	·03	22·4	288	Liquid.
		1319	26·27 g	7	21·80	·09	....	345	
				8	22·20	·15	....	366	
				10	22·23	·28	....	373	
				13	22·1[illegible]	·47	....	377	
				16	21·9[illegible]	·65	....	378	376·6
				19	21·79	·84	....	378	
I	10	954	948°	9	20·24	....	....	....	Immersion
		948	1186 g	10	26·00	·05	13·0	201	Solid.
		942	32·22 g	11	26·40	·12	....	218	
				12	26·52	·19	....	225	
				14	26·42	·3[illegible]	....	227	
				17	26·22	·5[illegible]	....	227	
				20	26·01	·74	....	227	226·6
				23	25·81	·94	....	227	
II	10	1364	1352°	9	17·18	....	....	....	Immersion
		1354	1194 g	10	23·70	·04	23·1	277	Liquid.
		1339	26·05 g	11	24·80	·10	....	330	
				12	25·20	·16	....	351	
				14	25·42	·29	....	368	
				17	25·19	·49	....	366	
				20	25·01	·68	....	367	367·0
				23	24·82	·87	....	367	
I	10	877	873°	0	14·83	....	....	....	Immersion
		873	1191 g	1	19·80	·02	11·9	173	Solid.
		870	32.20 g	2	20·30	·06	....	193	
				3	20·60	·09	....	205	
				5	20·48	·16	....	203	
				8	20·38	·26	....	203	
				11	20·23	.36	....	201	202·1
				14	20·13	·46	....	201	
II	10	1176	1166°	5	17·40	....	....	....	Immersion
		1164	1187 g	6	24·30	·04	19·2	281	Liquid.
		1158	25·97 g	7	24·70	·10	....	301	
				8	24·80	·16	....	308	
				10	24·75	·27	....	311	
				13	24·55	·44	....	309	
				16	24·39	·60	....	309	309·5
				19	24·21	·77	....	309	
II	10	1215	1197°	7	14·38	....	....	....	Immersion
		1191	1192 g	8	20·00	·03	19·9	239	Liquid.
		1186	25·95 g	9	20·80	·07	....	278	
				10	21·50	·12	....	312	
				12	21·55	·21	....	319	
				15	21·40	·35	....	318	
				18	21·26	·49	....	318	318·5
				21	21·13	·62	....	318	
I	10	782	781°	9	19·36	....	....	....	Immersion
		780	1189 g	10	24·00	·05	10·4	163	Solid.
		780	32·19 g	11	24·20	·12	....	173	
				12	24·18	·19	....	175	
				14	24·13	·33	....	178	
				17	23·95	·54	....	179	
				20	23·81	·74	....	181	179·7
				23	23·61	·94	....	181	

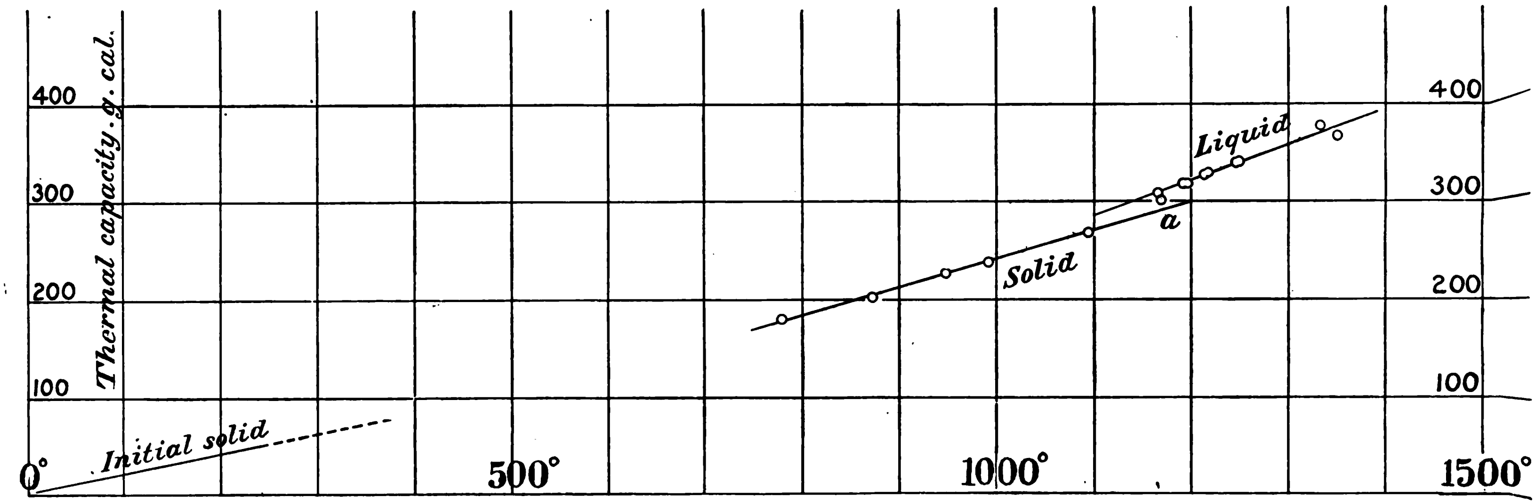
TABLE 17.—*Thermal capacity of diabase. Second series*—Continued.

No.	τ	Θ	Mean Θ M m.	Time.	θ	Correction θ	Correction h.	h.	
	°C.	°C.		minutes.	°C.	°C.	g. cal.	g. cal.	
II	10°	1204	1194°	8·5	14·54				Immersion
		1195	1195g	10	21·60	·03	19·9	307	Liquid.
		1183	25·90g	11	21·70	·08		314	
				12	21·70	·13		316	
				14	21·63	·23		318	
				17	21·49	·37		318	
				20	21·36	·51		318	317·9
				23	21·22	·66		318	
I	10	1177	1171°	8	19·88				Immersion
		1170	1192g	9	25·20	·05	16·7	182	Solid.
		1166	32·20g	10	28·20	·13		296	
				11	28·30	·21		303	
				13	28·07	·37		300	
				16	27·95	·62		304	
				19	27·62	·86		302	301·6
				22	27·37	1·10		301	
I	11	1106	1096°	0	16·28				Immersion
		1094	1195g	1	22·70	·03	15·5	224	Solid.
		1088	32·21g	2	23·60	·08		259	
				3	23·75	·13		266	
				5	23·69	·23		268	
				8	23·54	·39		268	
				11	23·39	·54		268	268·2
				14	23·24	·68		268	
II	11	1262	1248°	1	19·72				Immersion
		1244	1191g	2	25·90	·05	21·1	270	Liquid.
		1238	25·49g	3	26·60	·11		305	
				4	27·20	·17		336	
				6	27·11	·31		338	
				9	26·92	·50		339	
				12	26·73	·70		339	338·8
				15	26·55	·89		339	
I	11	1237	1218°	8	13·67				Immersion
		1216	1188g	9	20·60	·02	17·7	263	Liquid.
		1202	29·43g	10	21·40	·07		297	
				11	22·00	·12		324	
				13	22·05	·23		330	
				16	21·90	·38		330	
				19	21·75	·54		330	330·3
				22	21·60	·69		330	
II	11	1224	1215°	5	19·73				Immersion
		1215	1185g	6	25·20	·04	20·4	235	Liquid.
		1205	25·57g	7	26·40	·11		293	
				8	26·90	·19		320	
				10	26·90	·32		326	
				13	26·68	·54		326	
				16	26·49	·75		327	326·6
				19	26·27	·95		326	

For brevity the last observations have been averaged per three minutes, and under h the mean for the last 11 minutes is usually given.

Thus in Series I the difference of temperature from top to bottom of the crucible is as large as 61° at 1200°, but falls off pretty regularly to 6° at 829°. In Series II the corresponding mean difference is about 25° at 1300°, 20° at 1200°, 14° at 1100° and 1000°, and 10° at 900° and 800°. The error thus involved can not be greater than 2 per cent in the extreme case; but since the distribution of temperatures is actually measured, the error is probably negligible except at very high temperatures. I was inclined to infer that the greater constancy of the solid distribution as compared with the liquid was due to better conductivity in the former case (solid); but it may result as an equalizing effect of the tube, Pl. VII, Fig. 3.

Considering the observational work as whole, the data are quite satisfactory, seeing that an error of $\frac{1}{10}$° C. in the initial temperature of the



RELATION OF THERMAL CAPACITY (SOLID AND LIQUID) TO TEMPERATURE (°C.). SERIES I.

calorimeter must vitiate the result as far as at least 1 per cent. Hence the great care taken in finding this temperature. It is probable, however, that the real source of error is accidental and is encountered when the body falls out of the furnace into the water, particularly during the latter phase. Splashing, generation of steam, etc., then involve actual losses which can not be accounted for.

INFERENCES.

51. *Digest and charts.*—In Tables 18 and 19 I have summarized the chief data on a scale of temperature. The results are graphically given in the charts, Pls. VIII and IX, in which thermal capacity in gramme calories is constructed as a function of temperature. Straight lines are drawn through the points, showing the mean specific heats for the intervals of observation, solid and liquid. The letter *a* marks the region of fusion.

It will be seen that both in the cases of Pl. VIII and Pl. IX the solid points lie on lines which, if reasonably curved, would be nicely tangent to an initial specific heat of about .2 at 0° C. The grouping, in other words, is so thoroughly regular as quite to exclude the probability of any anomalous feature in the observed or the unobserved parts of the locus. In both charts the solid point near *a* alone lies markedly above the corresponding curve; but inasmuch as in my former work I found solidification to set in at 1,100° it is altogether probable that the occurrence at 1,170° is incipient fusion.

TABLE 18.—*Thermal capacity of diabase. Series I. Digest.*

Mean specific heat, liquid, 1200° to 1400°, ·350.
Mean specific heat, solid, 800° to 1100°, ·304.
Latent heat of fusion, at 1200°, 24gcal; at 1100°, 16gcal.

Solid.		Liquid.	
Temperature.	Thermal capacity.	Temperature.	Thermal capacity.
829	191	1274	358
880	204	1306	364
1001	242	1337	373
1025	253	1367	370
1078	263	1378	385
*1066	311		

*Incipient fusion? Tube sustained in the crucible.

TABLE 19.—*Thermal capacity of diabase. Series II. Digest.*

Mean specific heat, solid, 800° to 1100°, ·290
Mean specific heat, liquid, 1100° to 1400°, ·360.
Latent heat of fusion, 1200°, 24^{gcal}; at 1100°, 16^{gcal}.

Solid.		Liquid.	
Temperature.	Thermal capacity.	Temperature.	Thermal capacity.
°C.	gcal.	°C.	gcal.
781	180	1166	309
873	202	1194	318
948	227	1197	318
993	238	1215	327
1096	268	1218	330
*1171	302	1248	339
		1251	340
		1251	342
		1334	377
		1352	367

*Probably incipient fusion at the base of crucible (1177°).

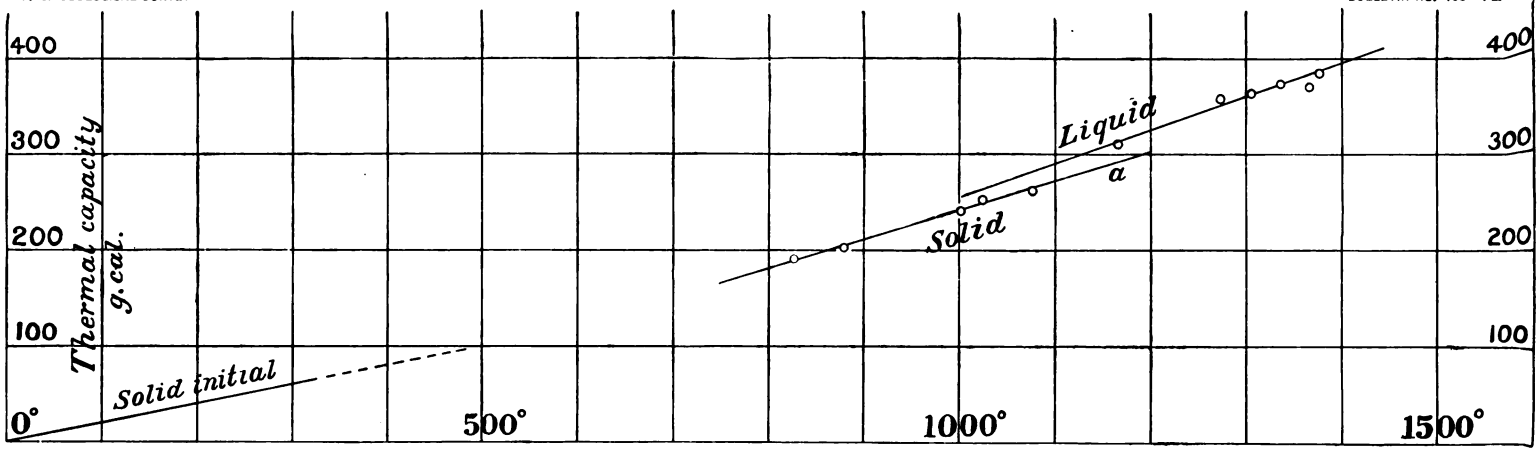
Quite the same regularity is observable in the liquid loci, remembering that in Pl. VIII only a single datum was taken for temperature, and that in Pl. IX the high-temperature discrepancies above 1300° are within the range given in § 50, and due to distribution of temperature.

52. Specific heat.—As regards the mean specific heat between 800° and 1000°, in Tables 18 and 19, it will be seen that the intermediate datum (·304+·290)/2 would satisfy both groups of points about equally well. A tracing of one group of points nearly covers the other, while it is to be remembered that the true locus must be slightly curved. The same remarks may be made for the liquid state. I have discarded elaborate modes of reduction, since the equation of the locus would be arbitrary, and since the values for specific heat are of no immediate bearing on the present inquiry.

53. Hysteresis.—Recurring to the suggestion of the preceding paragraph, it appears, since in my volume experiments I was able to cool down the rock to 1095° before solidification definitely set in, whereas, now, evidences for fusion do not occur before 1170° (at *a*, Pls. VIII and IX) that rock fusion must be accompanied by hysteresis[1] of the same nature as that which I observed with naphthaline, § 37. The magnitude of the lag is apparently 70°, and its pressure equivalent may be estimated as 500 atmospheres.

54. Latent heat.—In virtue of the fact that the upper end of the solid locus can be carried so near the beginning of the liquid locus, the datum for latent heat is determinable with some accuracy. A difficulty, however, presents itself in the determination of the true melting point, a datum which can only be sharply defined while the temperature of the crucible is quite constant throughout. I, therefore, state the conditions at 1200° and at 1100°, where the latent heats would be 24 and 16 gramme calories respectively, in both of the independent constructions of Pl. VIII and Pl. IX. This coincidence is in a measure accidental.

[1] Am. Journal, XLII, p. 140, 1891.



RELATION OF THERMAL CAPACITY (SOLID AND LIQUID) TO TEMPERATURE (°C.). SERIES II.

It may be noticed that a transitional temperature surprisingly near the region of fusion is apparently indicated.

55. The relation of melting point to pressure.—The first and second laws of thermodynamics lead to the equivalent of James Thomson's fusion equation, which in the notation of Clausius[1] is

$$\frac{dT}{dp}=\frac{T(\sigma-\tau)}{E\,r'},$$

where T is the absolute melting point, $\sigma-\tau$ the difference of specific volumes solid and liquid at T, r' the latent heat of fusion, and E Joule's equivalent. Combining the present series, *I*, with the former series, *III*, of volume measurements,[2] I obtain at 1200°, since $T=1470°$, $\sigma-\tau=\cdot0394/2\cdot72$ (where 2·72 is the density of the solid magma at zero) and $r'=24$,

$$\left(\frac{dT}{dp}\right)_{1200}=\cdot021;$$

and at 1100°, since $T=1370°$, $\sigma-\tau=\cdot0385/2\cdot72$, and $r'=16$,

$$\left(\frac{dT}{dp}\right)_{1100}=\cdot029.$$

Similarly combining the present series, *II*, with the former series of volume measurements,[3] *IV*, at 1200°, since $\sigma-\tau=\cdot0352/2\cdot72$ and $r'=24$,

$$\left(\frac{dT}{dp}\right)_{1200}=\cdot019;$$

and at 1100°, since $\sigma-\tau=\cdot0341/2\cdot72$ and $r'=16$

$$\left(\frac{dT}{dp}\right)_{1100}=\cdot026.$$

Hence the probable silicate value of dT/dp may be taken as ·025, and falls nicely within the margin (·020 to ·036) of corresponding data for organic substances (wax, spermaceti, paraffin, naphthaline, thymol). I may therefore justifiably infer that the relation of melting point to pressure, in case of the normal type of fusion, is nearly constant, irrespective of the substance operated on, and in spite of enormous differences of thermal expansibility and (probably) of compressibility. And in the measure in which this is true in passing from carbon compound to the thoroughly different silicon compound, it is more probably true for the same substance changed only as to pressure and temperature. In other words the relation of melting point to pressure is presumably linear.[4]

[1] Clausius: Wärmetheorie, I, p. 172, 1876. This is frequently called Clapeyron's equation.
[2] Chapter II, § 34.
[3] Chapter II, § 35.
[4] See my work on the continuity of solid and liquid (Am. Journ. Sci., Vol. xlii, p. 144, 1891), in which these relations are tested for naphthaline within an interval of 2,000 atmospheres.

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No. 104

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1893

UNITED STATES GEOLOGICAL SURVEY

J. W. POWELL, DIRECTOR

THE

LACIATION OF THE YELLOWSTONE VALLEY NORTH OF THE PARK

BY

WALTER HARVEY WEED

WASHINGTON
GOVERNMENT PRINTING OFFICE
1893

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DEPARTMENT OF THE INTERIOR,
U. S. GEOLOGICAL SURVEY,
YELLOWSTONE NATIONAL PARK DIVISION,
Washington, D. C., May 18, 1892.

SIR: I have the honor to transmit herewith a paper by Mr. Walter H. Weed, entitled "The Glaciation of the Yellowstone Valley north of the Park."

During glacial times the broad elevated region of the Yellowstone Park was deeply covered by ice, sending out its glaciers both to the north and south. The northern glacier, after emerging from the park, entered the broad valley below, near the junction of the Gardiner and Yellowstone rivers. In the present paper Mr. Weed presents the results of his investigations of the glacial phenomena of the valley. It is a valuable contribution to glacial geology, and, so far as I am aware, is the first detailed study of such phenomena in an inclosed mountain valley in the Rocky mountains.

I take pleasure in recommending Mr. Weed's paper for publication as a bulletin of the U. S. Geological Survey.

Yours, very respectfully,

ARNOLD HAGUE,
Geologist in charge.

Hon. J. W. POWELL,
Director U. S. Geological Survey.

OUTLINE OF THIS PAPER.

The present paper gives a detailed account of the glaciation of the Snowy mountains and of the upper valleys of the Yellowstone, whose deposits show an unusual phase of alpine glaciation.

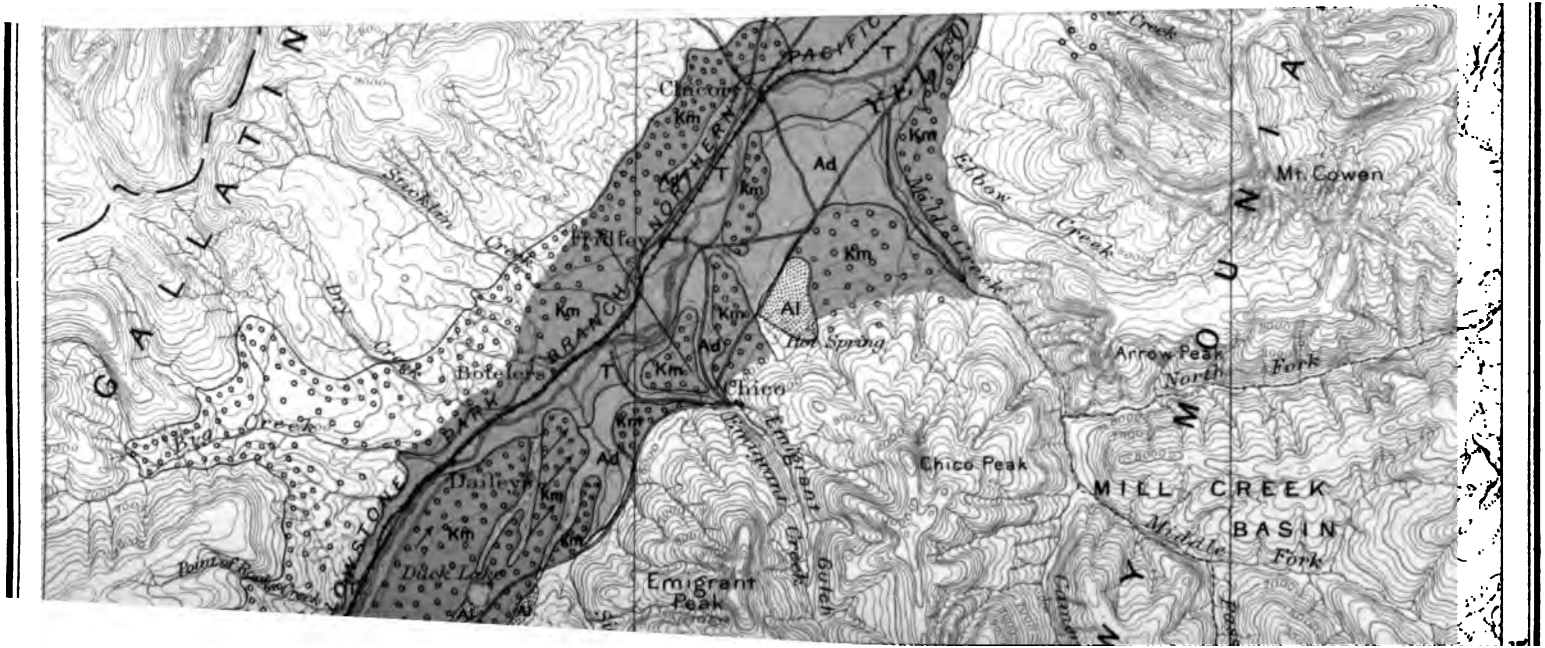
The evidence thus far gathered shows that a large body of ice, originating in the ice sheets of the Yellowstone National Park, pushed northward, filling the upper valleys of the Yellowstone and extending down that stream 36 miles north of the park boundary.

The high mountainous area east of the Yellowstone river, a large part of which is above 9,000 feet in elevation, was largely mantled by great snow fields and névés, above which the sharper summits projected as spires of rock, giving rise to great glaciers moving outwards down the valleys in all directions, forming the Boulder glacier and many small streams flowing toward the valley of the Stillwater, while other glaciers filled the valleys south and east and became tributary to the Yellowstone glacier. The high country about Haystack peak and Mount Douglas was the center of dispersion for this great ice field.

This evidence shows conclusively that there was no general system of confluent glaciers covering all the mountain ranges, but that even the greatest of these glaciers extended down the valleys a comparatively short distance and did not reach the general foothill country, while such considerable mountain masses as the Gallatin range and the high and rugged peaks east of the Lower canyon of the Yellowstone, held only local glaciers which nestled in the cirques about the crest of the range or rarely extended a short distance down the valleys. The area covered by glacial deposits is indicated upon the accompanying map.

These glaciers were all of the alpine type and present many resemblances to those now existing in the Mount St. Elias alps. The largest valleys—the Yellowstone and Boulder—were occupied by trunk glaciers, completely filling them and overriding their flanks, and receiving tribute from the lateral valleys where the ice bodies occupying them were large enough to reach the main valley. Throughout the entire field the higher mountain peaks rose above the névé fields, though the high plateaux and broader mountain summits show considerable glacial abrasion and were unquestionably covered by moving ice.

The evidence establishing the former existence of these glaciers consists of the varied forms of glacial sculpturing: Roche moutonées, canyon-broadening, rock-scoring and polishing, and the formation of rock basins; and the various types of glacial deposits, bowlder trains, blocs perche, the transportation of boulders from lower to higher elevations, moraines and kames, and the associated trains of gravel forming the system of river terraces, the formation of benches and terraces upon hillsides, and the cutting of canyons transverse to the mountain slopes and drainages in front of the glacier's termination. The striking contrast between glacial and non-glacial topography is splendidly exhibited in this field.



GALLATIN
MOUNTAINS
Mt. Cowen
Arrow Peak
North Fork
MILL CREEK BASIN
Middle Fork
Chico Peak
Emigrant Peak
Emigrant Creek
Emigrant Gulch
Chico
Hot Spring
Mill Creek
Elbow Creek
Clarion
Pray
Stockton Creek
Dry Creek
Big Creek
Boteler's
Daileys
Duck Lake
Point of Rocks Creek
NORTHERN PACIFIC
PARK BRANCH
YELLOWSTONE
Km
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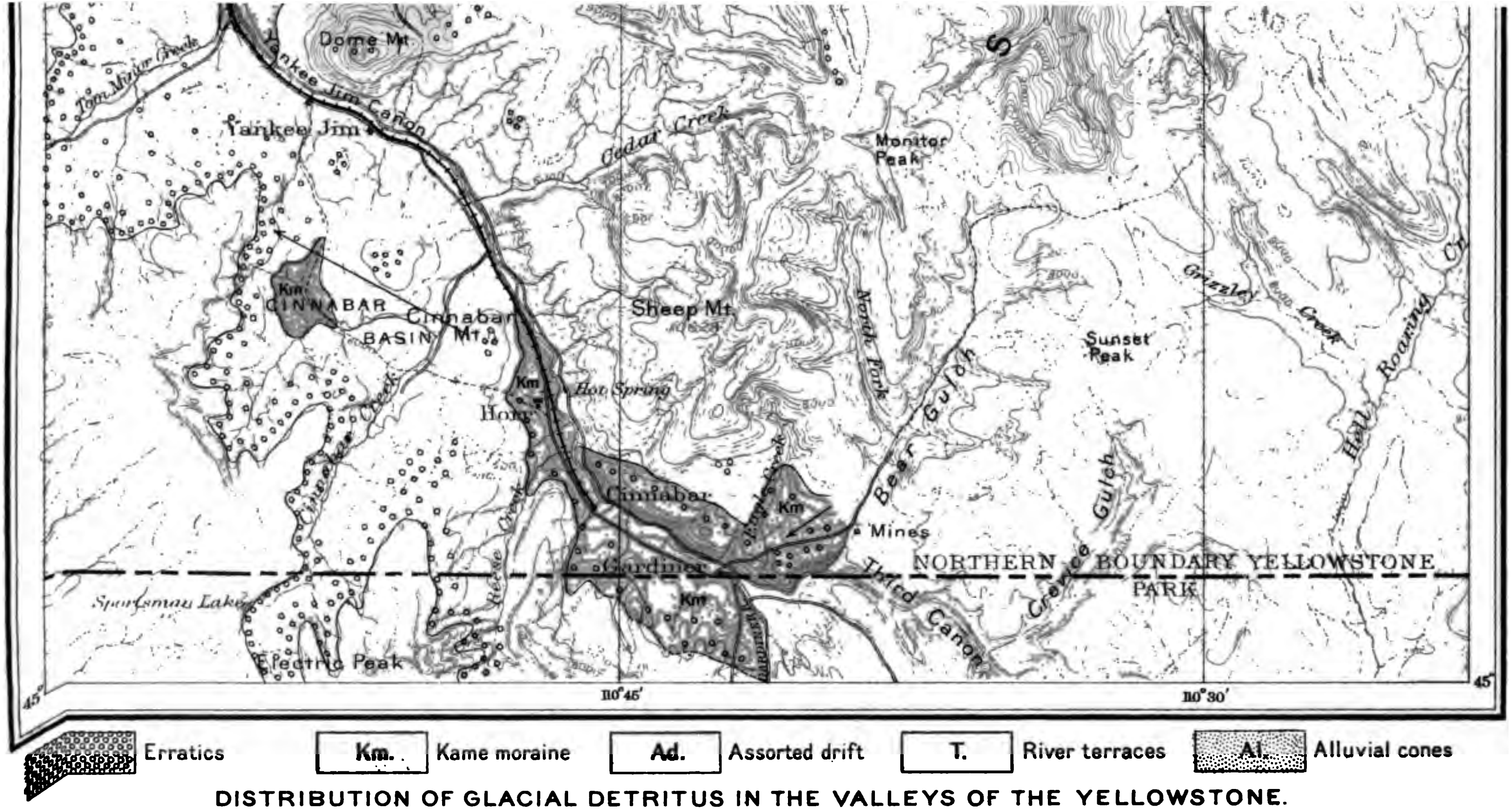

DISTRIBUTION OF GLACIAL DETRITUS IN THE VALLEYS OF THE YELLOWSTONE.

SCALE.

CONTOUR INTERVALS 200 FT.

THE GLACIATION OF THE YELLOWSTONE VALLEY NORTH OF THE PARK.

By Walter Harvey Weed.

INTRODUCTION.

The local glaciers of Quaternary times, of which evidences abound throughout the highest portions of the Rocky mountain cordillera, attained an unusually extensive development in that broad elevated region known as the Yellowstone Park. It was indeed the center of a considerable ice sheet whose glaciers spread out and down the valleys leading from this mountain region in all directions.[1] In the northern part of the park two streams of ice found an outlet for their united flow northward down the valley of the Yellowstone, and they have left impressive memorials of the power and size of this stream that at once attract the attention of the observant traveler on the way to the famous geyser basins of the park. The number and size of the erratic bowlders scattered so abundantly over the valley floor and perched high up on the mountain slopes, can not fail to impress the beholder, while the second canyon of the Yellowstone, known as Yankee Jim canyon, through which the river has cut its way to the broad mountain encircled lower valley, is a grand and perfect piece of ice sculpture that affords striking proof of the power and magnitude of the glacier which once filled the valley.

While studying and mapping the geology of a portion of the country north of the Yellowstone Park, under the direction of Mr. Arnold Hague, and for the United States Geological Survey, I found a long desired opportunity to study the glaciation of this interesting region.

[1] See Geol. Hist. of Yellowstone National Park, by Arnold Hague: Trans. Am. Inst. Min. Engrs. 1888.

GENERAL DESCRIPTION OF THE REGION.

The region herein discussed is a mountainous tract lying immediately north of the Yellowstone National Park, and drained by the Boulder and the Yellowstone rivers and many lesser tributary streams. The Yellowstone, rising far to the south, is here a noble stream of beryl green water which is joined by the Gardiner as it leaves the border of the park and flows northward through Cinnabar valley into a narrow gorge cut in Archean gneisses. From this canyon it darts out into a broad mountain flanked valley that is 30 miles long and from 3 to 6 miles wide, fancifully christened "Paradise valley," which it leaves through the lower canyon, or gate of the mountains, a narrow cut in the steeply upturned and folded Paleozoic rocks, to emerge into the great terraced valley that is the beginning of its long course through the Cretaceous rocks. The Boulder river, on the other hand, is a much smaller stream that heads in the snow banks about Haystack peak, and joined by numerous mountain torrents from the neighboring summits flows northward through a narrow canyon with walls 3,000 feet high, to join the Yellowstone in its great terraced valley about Big Timber.

THE YELLOWSTONE GLACIER.

The glacier occupying the mountain valleys of the Yellowstone has for convenience of reference been called the Yellowstone glacier. The ice stream had its source in the confluent ice sheets that covered the northwest portion of the National Park, and flowing northward overrode the lesser peaks about the boundary of that reservation and sent a great ice stream down the valley of the Yellowstone. This glacier, reenforced by a confluent stream from Bear gulch, completely filled the upper valley and exended far up on the mountain sides, completely covering such minor elevations as Cinnabar, Sphinx, and Dome mountains as it flowed northward to the low and broad valley below Yankee Jim canyon. This valley it occupied as far north as Mill creek, a total length of 36 miles from the park boundary. The width varied from 3 to 6 miles, and the depth in Yankee Jim canyon and the valley above it was 3,000 feet. As the névé fields of this great glacier were within the Yellowstone Park they will not be discussed in this paper.

In both the upper and lower of these two valleys this trunk glacier received tributary streams of ice. In the upper valley an ice sheet crept down from the mountainous region to the east, coalescing with another stream of ice from the park that pushed northward between Sepulchre mountain and Electric peak and filled the valley of Reese creek. In the lower valley the main glacier was reenforced by numerous tributary glaciers flowing westward down the great mountain valleys of Sixmile, Emigrant, and Mill creeks, whose united force deflected the northern end of the Yellowstone glacier westward against the foothills of the Gallatin range. The névé fields of these eastern tributary glaciers were the broad and high mountain summits of the Snowy range, each of the larger mountain gorges penetrating this rugged region, having been the bed of a glacier. The evidence shows that the névé fields of these tributary glaciers were of considerable extent and were confluent with those forming the head of the Boulder glaciers.

LIMITS OF GLACIATION.

In mapping the areas occupied by these ancient ice streams it has been found difficult to define the exact limits of the ice upon the mountains east of the Yellowstone, owing to the number of tributary glaciers and the gradual change from glacial to nonglacial topography, while the drift is generally of the same material as the rock upon which it rests. On the other hand, the drift deposits of the valley are readily studied, and the western limit of the drift is sharply outlined by the bowlders of gneiss and granite resting upon the rocky slopes of volcanic breccias. The gradually decreasing altitude at which this marginal drift occurs as we go northward from the park shows a rapid thinning of the glacier north of Yankee Jim canyon.

CINNABAR VALLEY.

Both the Cinnabar valley and the surrounding mountain slopes present many interesting evidences of glacial occupancy.

Bear gulch and Sheep mountain.—On the east the tributary glacier of Bear gulch has left a trail of rhyolite blocks from a hill some 8 miles above its mouth, showing that the ice crowded around this corner of the mountain, occupied what is now the head of Eagle creek and merged into the main stream as it overrode the flanks of Sheep mountain. It is a noticeable fact that the slopes of this mountain are abundantly strewn with erratics, particularly about the base, where the slopes merge into the bench made by the basalt and travertine sheets. The foot of these slopes is somewhat heavily mantled with drift, the bowlders being of moderate size and consisting chiefly of gneiss and granite, with many of rhyolite from Bear gulch; this detritus is arranged in crescentric loops with small alluvial flats behind them. The bench at the base of the mountain slope is but mildly glacial and free from bowlders. A till-like material is found in spots, mantled by gravels, and alluvium from the mountain slopes has largely covered the original glacial deposits if any were present. Owing to the frequency of the small recent faults which have broken and disturbed the bench glacial evidences are largely obscured. Rhyolite drift from the bluffs of Bear gulch forms a train encountered between the bluffs and the ranches of Eagle creek, and none was found south of this road (i. e., between the wagon-road and Bear gulch). The erratics generally are gneissic, occurring in clusters, and very abundant between Eagle creek and Bear gulch. A very considerable accumulation of massive bowlders upon the basalt bench north of the mouth of Bear gulch is supposed to be the work of the receding glacier.

Sepulcher mountain.—The west side of the valley evidences the conflict of the ice streams from the Yellowstone canyon and the Gardiner with the lesser stream coming down Reese creek, which by their union formed the trunk glacier of this valley. The upper slopes of Sepulcher mountain are littered with numerous erratics, the lower slopes in places mantled with glacial gravels and sands or carved into typical glacial hillocks by the abrasion of the ice. The drift accumulations of the mountain flanks are most conspicuous within the borders of the park. West of Gardiner the slopes attract attention by their rounded, mammillary forms, which, upon examination, are seen to be the result of erosion and not due to a covering of drift. The stage road from Gardiner to Cinnabar crosses a typical portion of this area in which the volcanic breccia composing the hilly slope is but scantily covered by drift, yet the topography is strongly morainal in its contours.

The valley bottom.—The immediate valley bottom contains much drift, which in the lower levels is of course terraced by alluvial action. The town of Gardiner is built upon such a bowlder-covered terrace, the erratics being chiefly gneiss. Chadborn's ranch to the north is built upon a well-defined moraine of great granite bowlders that outline the northern limit of the Sepulcher mountain moutonée forms. The valley bottom in this vicinity evidences various stages in the retreat of the ice sheet. North of Hoppe creek the stage road follows a depression with a level bottom some 125 yards wide between two ridges of bowlder drift.

In general the valley has been subject to considerable glacial erosion during the maximum extension of the ice, and the deposits of drift mark phases in the retreat of the ice. Mention should be made of the large deposits of glacial gravels forming kame-hills about the debouchure of Reese creek. The drift is all from the head of this lateral valley and brought by a branch ice stream pouring down the valley from the Sepulcher-Electric divide. From Cinnabar station to Cinnabar mountain the valley bottom on the west is wholly alluvial.

Cinnabar mountain.—The Cretaceous spur of coal-bearing rocks that terminates in the upheaved beds of Cinnabar mountain presents no special features of interest, though drift-covered hills of glacial gravels that accumulated at the base of Cinnabar mountain while the ice was crowding over its summit seem to prove that stagnant portions of the ice filled this place while the main current pushed through the gorge to the north or over the mountain top. Bowlders of gneiss and andesite resting upon the stratified beds prove that the ice passed over the summit.

From Cinnabar mountain to Yankee Jim canyon the course of the Yellowstone is northwestward, and that the northward-pushing glacier was deflected by the high mountains northeast of the river is evidenced by the drift carried from the Cinnabar mountain. The mountain slopes on the east side of the river show considerable evidences of glacial abrasion, benching, and the usual erratic blocks, but were not studied with the same detail as those to the west, which promised more definite and important results, but the drift shows that the ice overrode the slopes to a height of about 3,000 feet above the present stream.

The western side of the canyon, north of Cinnabar, to the gorge called Yankee Jim canyon, presents a different type of glacial erosion. The present canyon of Cinnabar creek is a post-glacial cut in a bench of granite whose surface presents fine examples of glacial polishing and scoring. A short distance northward the lower slopes are formed of the breccias which have been eroded by the ice. Seen from the slopes of Dome mountain this hilly area presents a peculiarly mammilated appearance. The hills formed of dark volcanic breccia of augitic rocks which when traversed is found to form rough craggy masses with a generally hummocky topography, there being no drainage and sharp basins lying between. It is a combination of glacial topography with post-glacial settling or land slides. Glacial gravels cap many of the knobs, especially east of the road, but erratics are rare. A peculiar feature of the northern end of this area where it runs into the basin at the south end of Yankee Jim canyon, is the fact that these hills run into ridges which are prolonged by glacial gravel. This gravelly drift shows blue quartzite, granite, and many varieties of andesite, but no basalt or rhyolite could be found.

A peculiar, tarn-like lake occupies one of the peculiar depressions in this foothill area, but is not dammed by glacial gravels. The slopes above these hills form the flank of a small elevation known as Sphinx mountain, whose glaciated summit, capped by numerous erratics, is 2,400 feet above the river. The andesitic breccias and basaltic flows forming the southern slopes of the mountain have been eroded by the ice into the characteristic knob and sink contours with very little small drift, though bowlders of granite with rarer erratics of sedimentary origin are abundant on flanks and summit. The eastern slopes are somewhat benched, and the northern slope shows a considerable accumulation of detritus forming glacial hummocks resting upon the rocky flanks.

Cinnabar basin.—Cinnabar basin is an elevated mountain park drained by the northern fork of Cinnabar creek. The valley of the main creek is a narrow cut with rocky walls and presents no points of interest in this connection, though evidencing the extent of post-glacial erosion in the walls of its inner gorge. The basin on the other hand is a preglacial valley greatly modified by its occupancy by ice and filled by glacial detritus. Looking down upon it from the surrounding mountain walls its smooth contours, pockets, hummocks, and rounded knolls and sinks show very clearly the work of the glacier in producing the present condition. Of the two streams which drain it the larger heads in a glacial amphitheater under the bold walls of the main summit of the range, and flows through a trenched channel; the other heading in a smaller mountain amphitheater, filled with hummocks of drift, meanders through a broad marshy area flanked by drift hills and gravel flats, and has not cut through the alluvium and drift which fill the valley bottom. These streams uniting form the north fork of Cinnabar creek. A transverse moraine has deflected this stream, where it joins Cinnabar creek, and forced the waters to cut a channel through gneiss, thus retarding the down-cutting of the stream above.

Transportation of bowlders to a higher level.—The high mountain ridge that forms the western wall of Cinnabar basin was covered by the ice to a height of 8,000 feet, the drift terminating abruptly at that elevation. The bowlders of this locality evidence an interesting example of the transportation of material from a lower to a higher level. At 7,400 feet the bowlder drift contains, besides the usual types of granite, gneisses, etc., many blocks of limestone and Dakota conglomerate, whose only source is Cinnabar mountain. None of these bowlders occur at lower levels, and as there is but one source it proves a movement of the ice over Cinnabar mountain westward. These bowlders are five and a half miles west of and 350 feet above their highest possible source. Bowlders of pink quartzite and shaly Cretaceous sandstone occur on these same slopes at a higher level. These bowlders furnish absolute evidence of the crowding of the glacier westward by the bend in the valley. As the constricted river gorge could hold but a small part of the glacier, the ice was forced to override Cinnabar and Sphinx mountains and filled Cinnabar basin, leaving a record of its margin as high as 8,000 feet on the western slopes. These western slopes which were not ice covered in turn deflected the ice stream, which in its course northward gouged out the beautiful little glacial valley followed by the trail from Cinnabar basin to the lower Yellowstone. At the south end of this cut the hammocks are of glacial drift. Two lakelets occupy depressions in its bottom, being confined by drift, but detritus is not abundant, consisting of scattered erratics, mostly of gneiss, with a few of andesite upon the adjacent slopes of volcanic breccia. The northern end of the cut is occupied by a small stream called Teepee creek, heading in a lakelet fed by a clear spring of water. The creek is actively cutting down a gorge in the mountain side, but does not follow the old course of the ice, which here crowded around the shoulder of the ridge separating Cinnabar basin from Tom Minor.

YANKEE JIM CANYON.

Yankee Jim canyon presents a very perfect and striking example of the eroding power of ice and of glacial sculpture.[1] It is a narrow gorge cut by the Yellowstone in metamorphic gneisses, through which the

[1] A charming description is given by Sir Archibald Geikie; see Geological Sketches.

river rushes in a torrent of beryl green quite unlike the placid stream above. The glacier which once filled this canyon and overflowed its walls has broadened it and rounded, planed, and polished its sides from bottom to top. The eastern wall, formed by the sides of a low, rounded knob known as Dome mountain, shows striated surfaces and ice-worn bosses, dotted with erratics almost to its summit. On the west the slopes above the polished surfaces of the immediate canyon wall are ice worn and are carved into typical glacial ridges and moutonnées, with a general bench structure to a height of 8,000 feet, or 3,000 feet above the river. Indeed, knowing the activity of disintegrating agencies in a climate where frost is an almost nightly visitor during the summer months and the winters are long and rigorous, it is surprising to find these evidences so fresh.

Erratics of gneiss are conspicuous wherever the surfaces have permitted their lodgment, and dot the ice-worn bosses at every altitude, so that it is certain that the glacier was 3,000 feet thick at this place and proves that this ancient glacier of the Yellowstone was of greater magnitude than has been ordinarily supposed.

The extreme erosion at this point of its course by the old glacier was due no doubt to a considerable contraction in its width, coincident with a narrowing of the valley bottom more than one-half, whereby a large part of the ice was forced to rise upward and override the higher slopes.

The morainal ridges of drift, the ice-worn bosses, and the erratics in the sag east of Dome mountain prove that a considerable portion of the ice, unable to crowd through the gorge, found an independent entrance into the broad lower valley of the Yellowstone. The sag itself shows considerable accumulations of detritus, forming benches and elongated ridges running north and south. Erratics were observed as high as 8,100 feet upon the spur east of this sag. Their absence above proves this to be the limit of glaciation.

EMIGRANT VALLEY.

Before passing through the lower canyon, the so-called gate of the mountains, to the broad and low valleys of the lower course, the Yellowstone flows through a broad valley, encompassed by mountains upon every side, a grand and beautiful intermountain basin, 30 miles long and from 3 to 6 miles wide. On the west the slopes rise gradually to the castellated crests of the Gallatin range; on the east the high pinnacle of Emigrant peak overshadows the valley, while the spires of Mount Cowen and its neighbors form a serrated wall, shutting in the northeastern part of the valley. Broad alluvial bottoms, with interosculating channels and islands bright with cottonwoods, mark the river's course. The broad terraces on either side are cut by numerous tributary streams issuing from their mountain gorges, supplying occasional farms, whose bright stretches of grain and tilled fields intensify the contrast between the fertile valley and the barren wilderness of the surrounding mountain slopes.

The geological observations hitherto made in this valley led the earlier geologists to suppose it to be the bed of an extinct lake, and the lake beds preserved beneath a protecting sheet of basalt show that such was once the case. A later episode in the history of the valley, and one that has given it its present surface, was the extension of the Yellowstone glacier northward, filling the southern half of the valley and depositing the glacial detritus, covering the higher levels and the gravels of which the great alluvial terraces are built.

The glacial stream confined within the narrow gorge of Yankee Jim canyon and the adjacent mountain slopes spread out and filled the broad bottom of this valley, depositing much of the detritus which the ice had transported from the mountains. These morainal accumulations are most interesting upon the eastern side of the valley, where considerable areas are covered by drift hills and kames, with abandoned channels of subglacial streams, and a chain of morainal lakelets add their charm to this peculiar scenery.

Upon the west side the immediate valley bottom is formed of alluvial terraces and the detritus of streams from the mountains, while the adjacent slopes are bowlder strewn and marked by a very striking and peculiar system of terrace lines.

Mountain canyons.—As the structural geology of the mountainous region to the east of this broad valley was studied by Mr. J. P. Iddings, I am indebted to him for notes upon the glaciation of the deep gorges which held large ice streams tributary to the trunk glacier of the Yellowstone. These glaciers pushing out and across the valley left their drift upon the extreme western margin of the glaciated area near Fridley's. All these mountain valleys show in their rounded slopes and ice-worn rocks and their general broadening that they have been sculptured by the ice streams they once held. (See Pl. III.) That these streams were of considerable size and thickness, is proven by the height to which the ice-worn bosses and ice-borne erratics have been found upon the mountain slopes. At the head of Sixmile creek a granite bowlder was found resting upon volcanic rocks at a height of 9,500 feet, thus proving that the glacier not only filled the great amphitheater at the head of this stream, but overrode its high encircling walls.

Morainal heapings.—The southern part of this great intermountain valley is covered with a superficial deposit of glacial drift that marks the area occupied by the ice. On the east side of the Yellowstone these morainal accumulations extend from the mouth of Yankee Jim canyon northward beyond the debouchure of Mill creek, interrupted only by the terraced drainage cuttings made by Sixmile and Emigrant creeks. As a whole this material is heaped into a tumultuous assemblage of knobby or mammillary hillocks with correspondingly sharp depressions, and the material is both unassorted and of kame-like stratification.

DUCK LAKE, A MORAINE-DAMMED SHEET OF WATER.

Morainal lakes.—A noticeable feature of the topography of this part of the valley is a chain of lakelets lying in a well defined depression between the base of the mountains and the drift-strewn summit of the basalt table. The largest of these bodies of water is known as Duck lake (see Pl. II), and, with its companion lakelets, belongs to the type of lakes due to dams of morainal material. This is perhaps most plainly shown in the case of the middle lakelet whose scalloped lobate form is due to the fact that the lake fills several adjacent morainal hollows. The drift is mainly small and partially assorted, forming typical kames.

East of these lakes a lateral moraine composed of quite large bowlders and more angular debris, largely of blocks 2 to 10 feet across, forms a prominent ridge running northward along the mountain side west of the stream tributary to Duck lake. It is the work of the ice as it spread out into the valley from the narrow bed of the canyon above and consists of fragments from the walls and slopes of Yankee Jim canyon.

Duck lake itself is a pleasing sheet of dark blue water, oval in outline, and forming an agreeable change to the eye after traveling over the monotonous moraine. The water is somewhat opaline at the windward side, the northern shores being gravelly beaches, showing a high water line some 2½ or 3 feet above the present level of the lake (in September). At the south end the shores are muddy and form the termination of a somewhat extensive marshy bottom that fills the depression between this lake and the smaller body of water to the south. The large drift is much more abundant immediately north of Duck lake than it is farther away.

North of Duck lake the wagon road follows a shallow, alluvial flat, separated from the bed of Duck lake by a train of detritus brought down by small streams from the adjacent mountain slope. Beyond this flat the kames attain their most characteristic development, consisting of gravels and sand rudely assorted and forming hillocks 15 to 20 feet high, capped by cobbles and bowlderlets chiefly of gniess and separated by sharp sinks and kettle holes. The road follows a gentle grassy depression formed by a glacial stream running to the northwest. This channel once held a good sized stream whose waters were burdened with silt and sand, with which it built up the terraced sides of the present grassy draw. That it is not an old channel of Sixmile creek is evident from its situation and the fact that such a stream would not desert so well formed a channel, and, furthermore, by the presence of an area of hummocky drift hills separating this old creek bed from the present drainage channels of Sixmile creek.

Sixmile creek at present flows in its old bed. A newer channel, now dry, being found on a terrace above the present creek marked by a line of cottonwoods and evidently occupied for many years. The broad gravel flat which now carries the water has been made by a stream much larger than the present creek, being in fact large enough to accommodate the Yellowstone itself. Between this channel and the basalt table to the west there is an area of morainal drift of some interest. A terrace about a quarter of a mile wide separates these morainal hills from the immediate gravelly flat of the creek, and the moraine terminates in the rear of this terrace in a steep bowlder slope very difficult to climb. The summit of the moraine is fairly level, thickly strewn with basalt bowlders from the basalt sheet to the west, with occasional erratics of gneiss and limestone. The bowlders average 2 to 3 feet in diameter and some 2 or 3 feet apart, resting upon smaller cobbly material. Small sandy benches occur occasionally, marking the site of small marginal streams. The north slope of this moraine is gently undulatory and knobby, while the southern slope is free from knobs and sinks, being a fairly level surface falling gently to the southwest, toward the old glacial stream channel heading in the moraine near Duck lake and holding a small alkaline lakelet. There is a noticeable decrease in the size of the bowlders as we go westward over this moraine. Between Sixmile and Emigrant creeks the moraine is a very gently accentuated knobby area, the hummocks rising but a few feet high, with many sandy level areas and a general inclination to the west of the entire area.

North of Emigrant creek the country is nearly similar to that just described, being but mildly morainal, the drift mainly under 12 inches in diameter and the larger bowlders being half buried in the smaller gravelly debris. Large bowlders are, however, frequently seen, with typical erratic form, striated sides, and beautifully polished, glistening surfaces. One fine intermorainic hollow was crossed that evidently served at one time as a temporary channel for a subglacial stream. This channel is 75 yards wide and heads in the drift hills. Beyond this channel the hummocks to the north are very rough and form a strip of country extending northward to a second subglacial channel heading in these hummocks and but 25 to 50 yards wide. Beyond here the hills are gently contoured, but typical in form and extend to the broad depression holding the lakelet shown upon the map. This depression is part of the glacial flood plain. Beyond the lakelet a narrow strip of moraine extends parallel to the river, nearly to the mouth of Eightmile creek, being separated by a broad, sandy terrace from another area of morainal debris, forming the hummocky lands lying at the base of the mountain slopes just south of the debouchure of Mill creek.

Basalt tables.—The central part of the valley is occupied by a mesa of lake beds capped by basalt. This forms two separate areas, of which the largest is on the east side of the river and extends from Point of Rocks northward to the mouth of Sixmile creek. The table is about 6 miles long and 3 miles wide, its summit being about 250 feet above the surface of the river. The top of this mesa shows occasional

MOUTH OF EMIGRANT GULCH, SHOWING GLACIATED MOUNTAIN GORGE OPENING INTO YELLOWSTONE VALLEY.

bare surfaces of the basalt generally as low domes of rock, 10 to 50 feet wide and 50 to 100 feet long, the basalt being smoothed and striated, the groovings running parallel to the river. These domes of rock are generally scantily scattered with bowlders. The summit of this basalt table shows in its striated and polished surfaces and its low moutonnée contour that it has been subjected to considerable glacial erosion. The retreating ice sheet has strewn its surface with bowlders and smaller glacial drift.

A thin mantle of drift, however, generally conceals the surface of the basalt. At the northern end the slopes are thickly scattered with bowlders of granite, black mica schist (rare) and occasional blocks of creamy white limestone, while a large proportion of the drift consists of basalt bowlders. The northern and western edges of the mesa are surmounted by sharp ridges of drift that rise 15 to 20 feet above the undulating sinks and swells of the general surface. A train of bowlders forms a ridge crossing the table to the southeast, and the general surface is paved with cobbles, the space between filled with small drift. In the central part of the table the bowlder ridges are well defined, running north and south with long narrow grassy depressions between. These hollows form a conspicuous feature of the summit; being filled with sand and alluvium and well grassed they form excellent pasture grounds that extend for a mile or two south, running into a confused heaping of drift with knobs and with small and disconnected sandy flats between.

The character of the drift covering the basalt table has already been indicated in the preceding paragraphs. The large bowlders which are particularly abundant upon the northern portion of the table contain a considerable variety of material in which basalt, identical in all respects with the rock beneath the drift, predominates. Bowlders of gneiss and schists are abundant, and occasional blocks of white quartzite and of pitted paleozoic limestone are very conspicuous. The glacial striæ show a movement down the main valley.

Glacial stream channels.—The existence of considerable streams flowing from the ice front is established by the many channels and sandy terraces associated with them, which cut across the drift hills or head within the morainal area. Besides these channels, formed by temporary streams flowing from the ice front, the streams from the east, notably from Sixmile and Emigrant gulches, have not always occupied their present beds, but in glacial times flowed in channels subsequently abandoned upon a recession of the ice or its complete disappearance. Thus the present wagon road from Findley to Chico follows a well defined and broad water course, cut in the sandy moraine and heading in a broad sandy plain at a level with the summit of the moraine and some 75 feet or so above the present bed of Emigrant creek. All traces of the stream channel end in this sandy terrace, which was the flood plain of the creek at the time the Emigrant gulch glacier had retired within the walls of the gulch. This channel was subsequently abandoned because silting up afforded an easier outlet for the water in the present course which has been cut down and forms the present channel of the creek.

Two small channels produced by subglacial streams have already been noted in describing the moraine north of Emigrant creek, but such channels are numerous. One of the largest, a rather shallow waterway with sandy terraces cutting the glacial flood plain and running north parallel to the road from Chico to Mill creek. Two cut deeply in the moraine south of Elbow creek, and others occur in the moraine area south of Sixmile creek. The deflection of Sixmile creek to the northward into the valley is caused by the accumulations of drift.

The largest of these glacial stream channels is probably that which lies back of the basalt table, a broad river bed heading in a low divide in the moraine above Duck lake, and extending down to the Yellowstone opposite Boettlers. It opens out into the great alluvial or gravel flat of Sixmile and Emigrant creeks, above which the moraine ridges rise with steep scarp slopes.

Another very marked channel lies east of this last and runs parallel to it, heading in a sandy terrace flat some 75 feet above and near the north end of Duck lake. This glacial (or subglacial) stream channel is one-third of a mile wide in its broadest part, with flat sandy bottom showing no water channeling. Near Duck lake the side walls of the coulee show longitudinal ridges or embankment-like heapings of bowlders. The floor of the depression is usually entirely of sand, but as the head of the ancient channel is approached the sand becomes coarser and grades into fine gravel which in turn becomes larger nearer Duck lake. In the lower part of the coulee bowlders are quite rare, but become more plentiful near the head. As is the case with the other ancient channels noted this one heads in sandy flat or plain in the moraine.

Drift deposits.—Upon the western edge of the river there is only a narrow strip of valley between the river and the foothill slopes, and this is entirely occupied by alluvial terraces from Tom Minor creek to Big creek. From Daileys to the northern limit of the drift, near Eightmile creek, the moraine covers the higher portion of the valley bottom above the alluvial terraces, presenting the usual types of conical hills of drift with an abundance of bowlders, many sandy flats and deserted subglacial stream channels. As already stated, the margin of the drift is readily traced upon the volcanic breccias forming the bare rocky hillsides which inclose the valley on the west. On the ridge north of Rock creek there is a well defined drift-covered bench at 7,740 feet. On both sides of Big creek the upper limit of the glacial detritus is about 6,800 feet. North of here the elevation rapidly declines until west of Fridleys the drift covers the low triangulation hill, beyond which it is limited to the valley bottom.

Terraces.—In the southern part of the valley these drift-strewn hillsides are characterized by a remarkable terracing of the slopes particularly prominent about the debouchure of Dry creek. The great terraces of Tom Minor basin and the equally definite terraces of Rock creek and Big creek, also lie within the limits of the drift and are coincident with the occupancy of the valley by the Yellowstone glacier. Several significant facts lead to this belief: These great benches are best marked where tributary valleys join the Yellowstone; they occur only upon the western side of the old glacier, and near its margin; they always occur within the bowlder-strewn area, and never above the limit of the drift, and they are cut in horizontally bedded volcanic breccias. The size of these benches will be appreciated by a look at the map showing their development about Big creek—a locality where they attain a very prominent development. On the north side of Big creek such a terrace forms a beautiful flat-topped grassy open bench, a mile wide. The surface has a slight gradient toward Big creek, and also to the east, passing imperceptibly upward into the mountain slopes in the rear. Bowlders are very abundant upon the eastern portion of this bench, and on the slopes immediately above it, but are rare west of the first fork of Big creek. This fork and the one to the west, have cut deep trenches in the bench, exposing sections showing that it is formed of andesitic breccia covered by drift, the latter being seen to be as much as 100 feet thick in certain places. The bench is continuous eastward to the valley of the Yellowstone; seen from the higher slopes to the south it is a broad flat, with the slope above it faintly lined by two narrow terrace-like markings, of which the uppermost corresponds to the upper limit of the glacial drift. No such bench was detected upon the spur south of Big creek; but granite bowlders resting upon the basaltic volcanic breccia show that the upper limit of the drift has about the same elevation.

Similar benches are extremely prominent in the basin of Tom Minor creek, and occur, though of much less extent, in the sides of the valleys of Rock, Dry, and Stricklin creeks. The Rock creek benches, though less extensive than those of Big creek, bear a similar relation to the drift. At this place the uppermost bench is the best defined, and corresponds to the upper limit of glacial detritus. The surface is fairly level, with pit-like hollows and occasional knobby hillocks rising above it, the general surface being covered with fine gravel and sands and occasional bowlders, in marked contrast to the bare, driftless slopes above. Below this bench the slopes show rugged steeps of breccia, proving considerable post-glacial erosion, though drift is abundant, both as bowlders upon well defined rocky benches and as ridges and groups of hills formed of glacial gravels. On the south side of Rock creek there is a narrow bench scoring the mountain slope and continues for several miles, though cut by drainage channels. This bench marks the upper limit of glacial drift, 7,800 feet, and is generally emphasized by a channel-like depression on its rear surface.

Striated valley slopes.—Associated with the great terraces just mentioned is a wonderfully fine series of terrace lines scoring the slopes below the limits of the drift. Back of Dailey's thirteen beautifully marked steps can be counted on the slopes west of the valley as shown in Fig. 1. It is at once apparent that these terrace lines are not part of a system of lake terraces. Their lack of horizontality, their lack of relation to other terraces puts this beyond doubt, and shows that they owe their origin to some other agency, either the ice sheet itself or marginal streams. These benches occur about the debouchure of Stricklin creek, where the higher lines form prominent scorings upon the slopes. They are all grassed and show no precipitous scarp. Their connection with

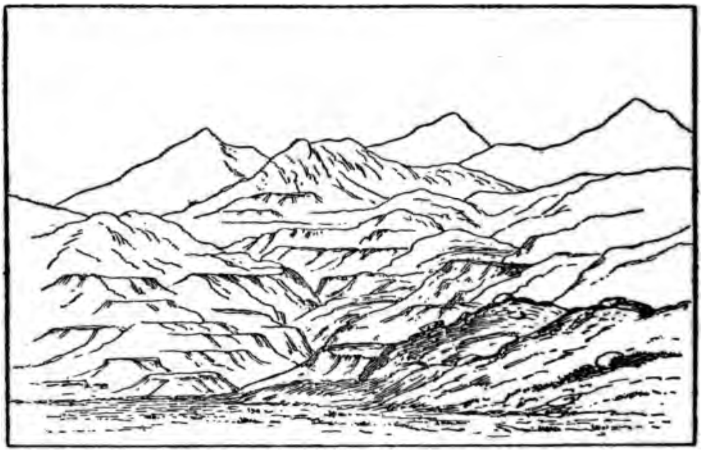

FIG. 1.—Glacial terraces of marginal area, valley of the Yellowstone (Geikie).

the great benches of Tom Minor, Big creek, etc., was a subject of inquiry, and it was found that the higher terrace lines about Dry creek follow the slopes around and run into the great benches of Big creek. Such at least appears to be the case when seen from the edge of the basalt table east of the river. The lower terrace lines do not show in the Big creek canyon, in fact would not be expected to, but the slopes about the debouchure of Big creek show definite and well marked terrace lines, only less prominent than those of Dry creek. To the south the higher bench lines show very markedly on the slopes south of Big creek, though uneven and lacking the beautiful uniformity of the Big creek benches. The slopes up to 400 feet above the river are generally hummocky hills, of breccia, with intervening sinks, resembling in a general and distant view a mammillated surface, in which the hummocks are quite large. Granite bowlders are abundant, and occur up to 10 feet in diameter. North of Dry creek the lower benches fade out in these slopes, the higher lines, corresponding to the faint lines seen on the slope north of Big creek, forming a prominent grassy bench above the mammillated contours of the breccia foothills and below the steep mountain slopes. This bench expands into a ⊿-shaped area on the south side of Stricklin creek.

These strongly marked terraces, which form such prominent feautures of the slopes inclosing the valley on the west, have no counterpart on the east side, where the moraines show an entirely different phase of glacial activity.

While these terraced slopes characterize the southern portion of the morainal area west of the river, where the valley bottom is low and occupied by alluvial terraces, the valley widens out north of Dailey's, and the morainal drift covers a gradually lessening portion of the foothill slopes, until west of Fridley the margin of the drift lies at the foot of the slopes.

In general, the morainal areas of the valley bottom are similar to those found upon the eastern side of the valley. Rolling hummocks of unassorted drift predominate, while there are many ridges of morainal gravel having a north and south trend with channel depressions between. There is a considerable variety of bowlder drift largely gneissic, but containing also some sedimentary material.

The basalt table of the eastern portion of the valley is represented here by much smaller and detached portions of the same sheet, also covering lake beds which, in this case, are shore deposits. This northern portion of the basalt sheet forms a narrow table north of Van Horn's, a mesa whose summit is a quarter of a mile broad, extending from Sheep creek north to the marsh back of Fridley. The level top is scantily strewn with drift, usually all small, only two large erratics being found, both at the extreme northern end. The drift is mainly andesitic, though white quartzite is prominent in the detritus covering the south end of the table.

The northern part of the morainal area shows a somewhat prominent terracing of the surface in general, though the upper benches are quite rolling. Large erratics are not very abundant, and are generally, though not always, found on knolls formed of smaller bowlders. There are many sandy alluvial flats and shallow basin areas, having no connection whatever with existing drainages. About a mile north of Fridley's the terrace bluff is cut by an old river channel, a distinctly marked waterway, with general northerly course and an elevation of 170 feet above the present wagon road. A morainal ridge with rolling surface lies between it and the terrace scarp to the east. Westward a bank of water-assorted gravel marks its borders. The surface of a higher terrace 230 feet above the river shows a drift moraine modified by water.

Foothill canyons.—A most curiously interesting feature of the drift-covered area is the presence of transverse canyons cut in the breccias directly across the slopes of the foothills. Their constant relation to the ice margin suggests that they had their origin during the period of glacial occupany of the valley. They are of considerable length, sometimes presenting several miles of unbroken walls. Their general direction is a most striking anomaly in the general structure and topography of the neighborhood, for the canyons cut across the slopes sometimes in apparent indifference to deeply trenched drains and rocky spurs alike.

In descending, the foothills which lie at the base of the Gallatin range west of Fridley and form the western boundary of this beautiful mountain valley, a remarkable tranverse cut or gorge is encountered just before reaching the hummocky surface of the valley bottom. This gorge is cut directly across the slope in the rudely bedded volcanic breccias with their intervening sheets of basic lavas. The walls are generally sharply defined, vertical, or nearly so, and show fine exposures of the rocks above a sloping pediment of talus blocks. In height the wall varies considerably, but frequently rises over 100 feet above the bottom of the canyon. The width varies also, but is usually from 50 to 200 yards from wall to wall, the bottom being more or less narrowed by the talus slopes which encroach upon it, and in places completely cover it. One more or less continuous cut was followed from the mouth of the second gulch south of Eightmile creek, south about 5 miles to Stricklin creek. Sometimes there are two or even three parallel canyons, in which case the highest is the largest and longest.

A peculiarity of these canyons is that they can not be seen from the valley, and when approaching the foothill slopes would not be noticed even upon close inspection until actually encountered. They form admirably sheltered refuges for the cattle pastured upon the neighboring hills, and have in the past served the same purpose for bands of bighorn and buffalo, both of which have been slaughtered here in great numbers, as is proven by the numerous skulls.

Only the very largest of the foothill stream channels cut across the upper canyon, while the smaller gulches open into it, the opposite wall being unbroken or marked by a slight depression. This peculiarity is best illustrated by giving my notes upon a portion of this canyon, which was followed for the purpose of ascertaining its extent and its origin.

Entering the north end of the gorge, at the mouth of the gulch south of Eightmile creek, it is at once evident that we are in a cut of most unusual structure. It is about 100 yards wide from wall to wall, the rocky ledges being 40 to 50 yards above its bottom, with sloping bases of talus loosened by frost from the vertical faces above.

The canyon bottom is fairly level between these talus slopes, and generally soiled and grassed, but varies much in width; at first it is narrow, some 25 to 30 yards across, but farther south it widens to 100 yards or more, extending as far as the mouth of the first gulch, cutting the slopes and western wall. This gulch is the bed of a stream, now dry, belonging to the normal drainage system of the foothills, and is the trunk of a ramifying system of deeply trenched little channels draining the slopes to the west, but all dry at this time of the year. The stream channel opens into the transverse canyon we have followed, but does not cross it, and in time of flood its stream must of necessity find its outlet through the canyon northward. Opposite the debouchure of this dry drainage way the east wall is unbroken, and about 100 feet high, a little less than it is farther north.

South of the lateral gulch just noted the canyon continues unbroken, but the walls approach nearer together, the bottom is filled with talus, and progress is difficult. The walls are here neither so high nor so precipitous as to the north. Half a mile to the south the walls recede, and the canyon bottom widens out to 150 yards, having a flat alluvium bottom, in the middle of which a rocky butte stands up some 15 feet high, like an island, in the flat. A sag in the eastern wall, some 10 feet above the alluvial flat, has at some time permitted the escape of the pent-up waters poured into this part of the canyon by a considerable gulch cutting the slopes a short distance west. It is this gulch which contributed the alluvial material forming the flat. The main canyon cutting extends up to and runs into the mouth of this gulch—a significant fact, if the drainage marginal to the ice sheet had anything to do with the cutting of this transverse canyon.

Following around this deflection of the canyon we observe that the foothill drain has not cut across the transverse canyon, its east wall being here 200 feet high, but has deflected it.

South of this gulch the canyon, though continued the same direction, is detached from the part already followed, and opens out to the main valley by a sag in the east wall. To the south the talus has filled up the canyon bottom, so that there is a rise of 50 feet. The walls are here only about 40 yards apart, and the talus forms inclosed basins of the canyon bottom. The west wall is a sheer face of breccia and basalt 125 feet high, with talus slopes overgrown with grass; the east wall is not so high, but as usually the case forms the highest part of a slope running gradually, often steeply down to the general slope of the morainal area. Here this slope was found to be cut by a smaller canyon parallel to and quite like the larger one which was followed, though it is but 25 feet deep and runs out in the knobby drift area to the north.

Throughout the length of the canyon so far examined, some three miles, there is a noticeable absence of stream gravel in the canyon bottom, except where quite clearly brought down by lateral gulches. Glacial drift is often entirely absent; sometimes occurs scantily in the canyon bottom, and very rarely was found on the immediate slopes west of the canyon. The next gulch to the south is the third thus far encountered, and the channel of a stream draining a considerable area of the slopes to the west for several miles back, in which it has cut a gorge 300 to 400 feet deep. At the mouth of this gulch the east wall of the transverse canyon is breached by a broad depression opening into the valley. To the south the canyon continues, but is rather narrow, and the walls, 100 feet or so in height, are flanked by much débris, often completely filling up the bottom of the gorge. About a mile to the south the canyon opens out into a flat some 200 yards, more or less, in diameter, the basin being separated from the main valley by a low sag in the east wall some 15 feet above the flat. South of this flat the canyon divides about a pillar of rock some 25 feet high and uniting continues, with walls somewhat diminished in height, to the first creek channel north of Stricklin creek, where it opens out into a gravel terrace with steep bowldery scarp 135 feet high. This dry creek is the largest drain thus far encountered, and it opens out into a well-defined alluvial cone, sloping gently to the east, and running into a flat that is part of an old river channel, and confined by morainal hills of drift, 25 to 30 feet high, on the east. Curious to see if the transverse canyon continued farther south, the alluvial flat was crossed and a continuation of the same canyon found and followed to Stricklin creek.

Relations of canyons to drift.—The relation of this transverse canyon to the glacial drift is most pertinent. It was noted—

First. That the slopes west of the canyon were bare of drift, and had not been covered by ice—this was positively established; in only one instance was any drift observed west of the cutting, and the bowlders formed a strip but a few yards wide.

Second. Drift is generally absent from the canyon itself and, if present, only in small amount.

Third. The slopes east of the canyon are heavily mantled with drift, both in the form of bowlders and as smaller material.

Fourth. This drift comes from the east, being gneiss and white talcose rock from the Snowy range, hornblende andesites, and sedimentaries.

Observations of the slopes east of the canyon were made at various points, and always showed the drift extending up to the very edge of the east wall of the canyon.

The larger drift was often found to be arranged in morainal ridges, running parallel to the canyon walls, and passing gradually into the more common knobs and sinks. As already stated, the slope east of the canyon is frequently trenched by shorter and smaller parallel depressions cut in the breccia. The morainal drift of the valley generally forms typical drift hills, rarely 25 to 40 feet in height.

Origin of transverse canyons.—After a careful study of these cuttings in the field I am still in doubt as to their origin. A recent faulting at first seemed most probable, and a resemblance to the fault fissures in the travertine and underlying basalt east of the river about Gardiner made this seem probable. Yet this type of canyon would not result from normal faulting, which would produce a single fault scarp. The bottom is, moreover, filled in a manner rather incompatible with this theory.

On the other hand the temporary character of streams flowing about the margin of ice sheet, scarcely warrants the belief that the canyon has been cut by such streams, even if aided by the drainages of the adjacent slope. The work necessary to cut down 100 or more feet across these transverse slopes, and through hard basalts and indurated, though easily eroded breccias, is not very onerous, and is easily performed to-day even by very small streams, but seems nevertheless to require more time than the existence of marginal streams could supply.

Glacial flood plain.—North of the limits of the drift, the valley bottom is filled with the glacial flood plain, largely terraced by the Yellowstone, but still retaining areas of its original surface. This plain has an elevation of 150 feet above the Yellowstone and opposite the mouth of Eightmile creek is an almost absolute level, the upward slope toward the moraine being very faint, as shown by a hand level, which gave a rise of only 8 feet or so in a mile. This is perhaps the most typical part of the morainal apron to be found in the valley. It is a flat extending from Mill creek to the Yellowstone opposite Chicory. An old glacial channel runs into it from the south, and the plain extends as far as the hot spring near Chico. On the west side of the river the alluvial gravels of Eightmile and of Trail creeks have obscured in part the great morainal apron, but its level surface appears north of Chicory, forming the great bench crossed by the wagon road and above the railroad terrace. The most striking view of the termination of the moraine is obtained from this plain, near Hayden—the foreground, of level hay fields, with water courses intensified by low groves of willow; a plain beyond, extending to the abrupt slope of the moraine front, whose sharp crested line of hills forms the background. Approaching the moraine, the surface of the plain is seen to be covered with rounded and smooth cobblestones, evenly distributed at some distance from the moraine, but arranged in channels near the hummock hills.

The moraine front rises abruptly as steep hills, with bowlder strewn fronts, no bowlders being seen on the overwash plain. No sand is seen on the surface of these moraine hummocks. The wagon road up the valley enters the moraine before crossing the middle branch of Eightmile creek, and passes an intermorainic hollow or channel, 250 yards wide, between the two ranges of terminal moraine hills, a second chain of hills being crossed by the road before reaching the modern channel of Eightmile creek.

Alluvial terraces.—North of the moraine of the Yellowstone valley, and beyond the immediate apron forming the moraine front, the valley is filled with morainal gravels, in which the river has cut well defined terraces. The best examples of river terracing occur within the morainal drift area, especially about Fridley. Immediately back and west of that settlement the valley presents series of alluvial terraces, the highest 160 feet or so above the river, but the moraine forms well defined terraces, with rolling hummocky surface at 170, 190, and 230 to 240 feet above the town.

Opposite the railroad station called Chicory there are three well marked river terraces at 25, 50, and 150 feet, respectively, the uppermost being the morainal apron or flood plain. The same terrace appears on the west side of the river, to the north of Eightmile creek.

In the lower valley, local ice streams from Elbow, Barney, Pine, and Deep creeks formed moraines extending down their canyons and forming prominent ridges about the debouchure of the creeks, particularly Pine creek, where the moraine comes down to the road. As a whole, however, this eastern side of the valley shows no terracing, but is an apparently gentle, continuous slope from the base of the mountain down to the river edge.

This lower valley is really very beautiful, with grand mountains on the east, fertile farms, and abundant water supply. Seen from a limestone knob standing up from the plain near the mouth of Deep creek, the valley to the south is a flat, alluvial plain, a few groves of cottonwoods marking the river's meandering course, and lines of trees showing where the plain is crossed by tributary streams from the mountains. The valley bottom slopes up from the river on the east side almost imperceptibly, till 1,000 to 1,200 feet above the Yellowstone, the slope really being formed by adjacent alluvial cones. At the foot of the mountains a heavy growth of pine timber darkens the slopes, extending up the mountain sides as far as the trees can obtain foothold, and dotting the rugged buttresses and crags of the lower part of this "Rough-enough" range.

The alluvial cones or foothill slopes show no benches nor definite morainal ridges save that already noted at Pine creek. They are without doubt largely formed of morainal gravels washed down when small local glaciers occupied the mountain gorges. Between Pine and Deep creeks these alluvial trains with definite morainal ridges reach far up into the mouths of the canyons. Where Deep creek debouches from the mountains the slopes show several well defined benches formed of great granite bowlders; but the benches do not extend more than one-sixth of a mile beyond the canyon, running out in the uppermost part of a perfect alluvial cone.

The high mountains east of the lower valley are deeply trenched by narrow canyons that are almost free from glacial detritus. This is easily explained by the torrential character of the drainages which carried the debris down and banked it up at the mouths of the canyons in the high bowlder benches just noted. These fade rapidly into the heads of steeply sloping broad cones of alluvial gravels and long wash slopes.

On the west side of the river the valley bottom is well terraced and bounded by gentle hills in which there are no large streams. These slopes are generally bare and grassy, occasional pines emphasizing a rocky outcrop or defining the basin at the head of some small dry drainage way.

Below the valley the river flows between steep rocky walls of upturned sedimentary rock, showing a most beautiful section of the Paleozoic beds. The river is cutting down its bed slowly at present, and flows in a number of interosculating channels, separated by numerous islands green with grain or covered by groves of stately cottonwoods.

Discussion of evidence.—It is apparent from an inspection of the accompanying map, upon which the outline of the drift has been indicated, that the glacier which occupied the valley bottom, great as it was, and coming from that great center of dispersion, the Yellowstone park, was a very local ice stream. Yet its influence upon the topography, and, to some extent, the scenery of the area covered by it, warrants this extended account of its work.

In the upper mountain valley the glacial detritus is very small in amount, in fact only insignificant deposits have been left in certain sheltered positions, though the retreating ice dropped bowlders pretty generally over the entire area covered. The work of the ice in this part of the field was mainly that of erosion. The amount of this erosion it is impossible to tell. Upon the granites and gneisses the ice has left an unmistakable record of its power to plane and polish, but the volcanic breccias show only the broader features of the erosion performed by ice, the rock not being suitable for the preservation of the finer features of such work, but probably yielding somewhat readily to the plucking action of the ice.

In the lower valley we have direct evidence of an advance of the trunk glacier as far north as Fridley, in the glacially planed surfaces of the basalt sheets found in the center of the valley. It is supposed that horizontal rock layers, such as these, do not present the most favorable conditions for glacial erosion and striation, yet these surfaces afford well preserved evidences of both in their low, rounded, and polished domes of rock, and their north and south striæ, which must have been formed by a somewhat thick sheet of ice moving northward. In support of this we have the presence of basalt bowlders, undoubtedly from this valley sheet, in great abundance, north of the eastern table. These bowlders are generally well glaciated, for the rock being very hard and resisting weathering well, preserves such traces in an excellent condition.

As these bowlders occur for several miles northward from the basalt table, and at elevations almost equal to that from which they come, it is evident they have been plucked and carried forward beneath the ice, and they form further and confirmatory evidence that the ice stream, thinned as it must have been at this point, was still capable of doing a considerable work. It is evident that these basalt bowlders, like those torn and transported from Cinnabar mountain, originated and were transported wholly beneath the ice, and were not frost-riven fragments from peaks and arêtes projecting above the ice. They thus afford a demonstration of the efficiency of the ice stream as an erosive agent. It should be remembered in this connection that the fall of the valley is only some 200 feet from the mouth of Yankee Jim canyon to the extreme border of the drift, some 18 miles, and that the glacier, crowded between the mountain slopes and in the gorge of Yankee Jim canyon, expanded out to at least twice that width in this broad valley.

The quartzite drift and limestone bowlders found on the basalt tables, may evidence a pushing westward of the tributary glacier of Emigrant creek, following a recession of the valley glacier. At any rate the absence of these forms of drift south of this part of the valley is certainly significant. It is to such an advance that we must ascribe the morainal heaping on the eastern basalt table, though the ridges and accompanying intervening channel-like vales may conform indirection to the movement of the ice stream, as has been in the case in the ridge moraine of the Boulder glacier. It is believed that the great benches or terraces of Big creek, Rock creek and Tom Minor creek are not of glacial origin, and that the coincidence of the drift limit with their borders possesses no especial significance. The narrow bench lines striating the slopes about the mouths of Stricklin and Dry creeks, are in part at least (see Fig. 1) the work of streams marginal to the ice.

THE BOULDER GLACIERS.

General description.—The mountainous area immediately north of the Yellowstone Park and bounded by the Yellowstone river on the west and north is an alpine region abounding in grandly beautiful scenery. It is characterized by a great plateau of Archean gneisses, deeply trenched by the many streams which have their sources in the snow banks and lakes of their summits, and by high peaks of volcanic rocks whose peculiar erosion adds pleasing variety to the types of mountain scenery afforded by the limestones to the north and the Archean masses on which they rest.

This block of mountains was very generally covered by ice during the period of glaciation, which sent ice streams down the principal gorges and mountain valleys. Both the plateau summits and these mountain canyons present undoubted evidences of the work of the ice in producing the present configuration of the surface.

To the northward there are two ice streams occupying the principal valleys, those of the Boulder and its tributary, the West Boulder. The path of these glaciers and the mountain area in which they originated present us with very interesting and typical examples of alpine glaciation.

The pri ncipal stream draining this alpine area is the Boulder river. Heading in the many lakelets which lie nestled in the mountain basins about Haystack peak, the stream flows rapidly through a narrow gorge which it has cut through the granites in past glacial times to the point where its volume is augmented by a considerable stream called Bridge creek. From here northward it flows in a bowlder-choked channel through the great canyon of the Boulder, whose glistening walls of polished gneiss rise 3,000 feet high on either side. For the last few miles of its course through this impressive gorge the stream meanders somewhat slowly through a network of channels bordered by dense growths of spruce and fir, with thickets of brushwood; then quietly glides through boggy meadows past the cottonwood-covered islands at the gate of the mountains. Immediately above the Natural Bridge the stream flows in a limestone bed, in which it soon cuts a rapidly deepening gorge as it flows northward in a series of rapids and cascades to disappear in a snowy white feathery fall of 25 feet into the tunnel of which the Natural Bridge forms the portal. Emerging a hundred yards to the north and 100 feet below, the stream falls into a tranquil pool at the head of a gorge that is a mile or so long and has limestone walls 100 feet high. The roof of the first short tunnel is a dry river bed, the floor of a gorge that is a continuation of the picturesque cutting above the Natural Bridge. The numerous potholes and waterworn ledges show that the river must flow over this channel in time of flood, to fall over a vertical wall into the pool 100 feet below. The beautiful canyon cut in a low limestone anticlinal north of this is, however, immediately deserted by the river, which at once enters a tunnel in the western wall, only to emerge at the northern end of the canyon. That this gorge is occasionally occupied by the river is attested by the driftwood and gravel in its bottom; but the great slopes of talus, where firs 60 feet high are growing, show that such occupancy is but temporary.

The valley of the Boulder begins at the north end of this deserted river canyon, and is cut in the Cretaceous sandstones and shales, resting upon the steeply upturned Paleozoic limestones which flank the Archean gneisses, and whose upturned ledges form the end of the canyon. This valley is about three-fourths of a mile wide, and flanked by walls of Cretaceous rocks, a few hundred feet high on either side. In this upper valley the river peacefully meanders in graceful curves and ox-bow loops, through broad alluvial flats covered by cottonwoods, until it is joined by the West Boulder. Here as it leaves the morainal drift the valley immediately broadens out to a nearly uniform width of a mile, and the bottom lands and terrace flats are of greater extent and generally occupied as farms. In this part of its course the river flows more rapidly, dashing against the many great bowlders which fill its channel, or cutting the bluffs of volcanic breccia out of which the valley has been carved farther northward.

This lower valley is extremely beautiful and picturesque; its softer contours and bright green slopes being in pleasing contrast to the wilder and grander scenery of the upper part of the river's course. The walls to the west are often picturesquely pinnacled and buttressed by the erosion of the breccia, while on the east of the stream are broad and charming alluvial terraces. A broad and distinctly cut bench scores the slopes of the east, and runs into a broad gravel covered terrace, which at the mouth of Cherry creek is 250 feet above the river. It forms the beginning of the terrace system of the Yellowstone through which the Boulder has cut its way to join that stream in the valley about Big Timber. In this lower part of its course the stream is bordered by a great terrace formed of flats of bowlders and gravel, brought down by the stream from the morainal drift of its upper course.

Like most mountain streams the river has a descent so great that it has removed and carried down the greater part of the morainal débris which choked its course, a work that is still in progress.

Névé fields.—It is impossible to define the névé fields of this region because the summits of the high plateau, over 10,000 feet above the sea, show glaciated surfaces which can not be differentiated from those found at lower elevations where there is undoubted evidence of true glacial movement in the general topographic relations, and where the summits and mountain basins show morainal accumulations in sheltered nooks that have undoubtedly been left by the shrunken remnants of the greater glaciers. These summits are characterized by an abundance of lakelets occupying rock basins, or occasionally held by dams of morainal material.

The gorges which head in these basins and amphitheaters, are typically glacial in form and show good examples of ice scoring when they are cut in the gneisses. Upon the divides and ridges at the heads of the gorges, bowlders are frequently found as instanced at the head of Sixmile creek, where a gneiss erratic, a foot in diameter, rested upon volcanic breccia, at 9,400 feet in a position which it could only have reached by transportation across an intervening valley several hundred feet deep. It is significant as evidencing a general movement northward of the ice sheet covering the central portion of the range as well as the more common movements down the mountain gorges.

The observations of Mr. Iddings, by whom the general geology of this mountain tract was studied, showed that glaciated surfaces prevail about the heads of all the more important drainages the slopes being characterized by glacial striæ, running away from the divide and down the valleys.

My own observations show similar glaciated areas at the head of the Boulder about Haystack peak. Haystack basin, a mountain-top terrace, shows beautifully glaciated surfaces of diorite with local drift deposits and occasional erratics from the neighboring peaks. Two glaciated lakelets make this basin an attractive camp. The slopes

GLACIATED WALL OF BOULDER CANYON, SHOWING OCCUPANCY OF ENTIRE CANYON BY ICE.

of Haystack, crossed by the trail from the gold mines, show good examples of glaciated ledges roughened by plucking.

Canyons.—From the Haystack mines northward to Bridge creek, the canyon is decidedly rugged, with a terraced bottom such as is common in the glaciated canyons of the Sierra Nevada. The adjacent slopes are rugged, and though showing well glaciated surfaces lack the general rounding so prominent in the canyon farther northward, and are definitely though irregularly benched. These surfaces are barer than those to the north, and apparently more freshly glaciated. The slopes have been bared by avalanches, whose paths are plainly marked by areas of devastation, in desolate contrast to the flower-covered opens or the picturesque pine groves of the neighboring slopes. The stream flows through a channel, very narrow, steep and rocky; there are no alluvial flats, though well-wooded benches covered with talus extend along the canyon bottom.

The first and in fact the largest open or park of the canyon, called Hicks park, is situated about ten miles below the mines. The stream leaves its rocky bed a few miles below this and flows thereafter over a bed of bowlders and morainal debris filling the valley bottom. In fact the quantity of debris left by the retreating glacier is so great that the stream, notwithstanding its steep descent, has been unable as yet to clear it out. Below Hicks park the canyon walls are much nearer together than farther north and show beautifully glaciated moutonnéed surfaces. (See Plate IV.) Considerable morainal accumulations fill the canyon bottom at the mouth of a large stream from the west, the open hills being known as Lick park. Two lakelets fill hollows in an old river channel in this moraine, and sharp ridges of debris fill the bottom. Below this point the canyon walls recede, and the glacial U shape is very prominent.

This canyon of the Boulder is extremely disappointing to the traveler. The walls below Lick park, though rising to great altitudes, 3,000 feet and more above the stream, are receding, generally wooded, and do not fulfill the promise of rugged beauty given by the entrance to this great gorge. This is no doubt largely due to the general roundness caused by glacial erosion. The bosses of rock in the canyon bottom and the upper walls alike show glacial rounding and polishing shown in Plate IV, and the resulting smoothness is a disappointment so far as scenic beauty is concerned. The limestone slopes at the mouth of the canyon and about the Natural Bridge show the result of the glacial erosion of sedimentary rocks. From here northward the ice has filled the valley trough and overflowed the walls covering the adjacent slopes. Its margin is easily defined by the rather heavy deposits of drift and débris, but it is evident that there was little, if any, erosion of these surfaces, for the ledges of limestone show no abraded surfaces, nor does the drift farther north contain fragments of these rocks. This failure to erode the sedimentary rocks is the more remarkable since the ledges dip at an angle of some 30° in the direction of the movement and the alterations of shale and sandstones have brought the ledges of harder rock into bold relief as hogback ridges.

Moraines.—In this lower part of its course the river has removed most of the morainal débris from the valley bottom, and it is only upon the surfaces above the valley wall that the glacial débris forms noticeable morainal heapings. These extend northward to the mouth of the west fork of the river.

Notable morainal heapings occur on the East Boulder in its upper mountain valley, but present no claims to novelty. A high monoclinal wall prevented their extension northward into a basin filled by glacial gravel sands, an attractive area, upon which the white settlers look covetously. It is a broad, open basin, the center being a nearly level gravel terrace through which the streams heading in the mountains to the east have cut down some 100 feet without reaching bed rock. To the south the slopes are not glacial, the limit of the drift being about the edge of this alluvial basin. From here to the mouth of the east fork the drift covers the lower slopes east of the stream, but does not surmount to rocky ledges of Cretaceous sandstone outcropping above. The area between the East fork and the Boulder is a low triangular doab heavily covered by drift. A scar made by the river shows in one place a thickness of 50 feet of stratified sand and gravel, overlaid by drift, but erratics are rare.

The glacier that occupied the valley of the West Boulder did not extend as far northward as that of the main stream, and ends just north of the point where the McLeod wagon road crosses the stream.

The ice stream which filled the valley of the West Boulder overflowed the walls of this valley, and left its morainal debris to mark its limits on the adjacent slopes. This drift forms a narrow belt, in general parallel to the stream, resting upon the eroded surfaces of the upturned and flexed beds of the upper Cretaceous. Where it is crossed by the McLeod road near its northern termination, it shows the usual knob and sink topography of these moraines, the hillocks of the large drift, the sinks, often the beds of dried ponds. The bowlders average 3 to 5 feet in diameter. This part of the moraine shows water channels, a feature that is absent from the moraine on top of the bluffs upstream. On the east side of the river the moraine terminates in a considerable accumulation of debris forming a tumultuous assemblage of hummocky knobs and sinks, the material being quite coarse and but little rounded, and manifestly largely from the surface of the ice. The summit of this moraine is formed of some ten parallel bowlder ridges, with grassy, bowlderless troughs between, some 25 to 30 feet wide.

The moraine upon the west side of the river presents few points of interest. Back of the "Blue Rim" cliffs it forms a considerable lakelet by damming the natural slopes, and its margin is very sharply defined upon the Laramie sandstones. As a rule the surface of this moraine is very rough, the drift varying greatly in size, and including many large blocks principally of granite, gneiss, and schist. Near the mouth of Davis creek the drift contains abundant bowlders of limestone and of conglomerate, but these rocks do not extend more than a mile north of their outcrops. Immediately back of the "Blue Rim" cliffs there is a moraine flat 200 yards wide at the top of the bluff, and back of this the usual hummocks prevail.

The country east of the river is very generally heavily mantled by morainal debris for some distance back from the edge of the bluffs. The table-land south of the McLeod road shows a fine alluvial area that is very fertile, owing to the damming back of the drainage by the moraine. The moraine itself is here very rough, and dotted with eight lakelets. Further south this character is preserved to the mouth of the mountain canyon, corresponding to the outcrops of the Carboniferous rocks. At the mouth of this grandly picturesque mountain gorge the canyon bottom is choked with drift and the stream is yet cutting down through the drift, and has at some late date formed a lake immediately above the mouth of Davis creek, whose grassy flats form a fine hay ranch.

Terraces.—Although it will be seen from this account of the morainal accumulations of the Boulder, and its branches that the amount of débris is considerable, yet it is small compared with the erosion which the ice has accomplished. In fact, the accumulations of the West Boulder, though not extending so far northward, are greater than those of the main stream. The question at once arises what has become of the eroded material?

Although these glaciers had a length of 10 to 20 miles, there are no great morainal embankments to show their former magnitude, such as abound in the Wind River mountains and the Hoback ranges south of the park. The reason is perhaps to be found in the great terraces of gravel that border the Yellowstone. The lower course of the Boulder river is marked by terraces of assorted drift, but the narrowness of the valley has not favored the preservation of the great trains of debris which undoubtedly were carried down the valley from the termination of the glacier. The larger part of this material was probably swept northward by the flooded stream, and helped to build the broad and extensive terraces of the Yellowstone. It should be noted, however, that there is a considerable terrace on the east side of the Boulder, corresponding in level to the great upper terrace of the Yellowstone, south of Big Timber. It is a very level area about a mile across, in greatest extent, sloping to the north downstream, covered by well rounded cobbles and gravel of gneiss, limestone, shale, conglomerate, and other rocks found to the south. This terrace is, however, but part ot the great system that forms so prominent a feature of the piedmont country of this region and record an elevation and erosion, subsequent to the maximum of glaciation.

The Boulder glacier was the usual type of mountain ice stream, common in the Rocky Mountain region south of the limit of the great Cordillera glacier described by Dawson. It differs but slightly from those that streamed outward from the deep-cut gorges of the Crazy mountains, where the source of supply was small and local.

Further studies are in progress in other parts of the Cordillera, from the Canadian line southward, and also of the isolated groups of mountains, the Crazies, Highwood, and others that form such striking features of the plains country east of the main ranges. It is believed that the results will contribute much of value to the history of the Pleistocene in this region and throw light upon some of the little understood problems that confront the geologist.

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DEPARTMENT OF THE INTERIOR,
UNITED STATES GEOLOGICAL SURVEY,
YELLOWSTONE NATIONAL PARK DIVISION.
Washington, D. C., July 18, 1892.

SIR: I take pleasure in transmitting, herewith, a paper by Mr. Walter H. Weed, entitled "The Laramie and the overlying Livingston Formation in Montana," with a report upon their Flora, by Mr. Frank H. Knowlton.

In working out the geology of the Cordillera there are no more important chapters than those that relate to the physical history of the Laramie and the overlying formation. These rocks are well developed in the Yellowstone valley, between the Bridger, Snowy, and Crazy mountains, and Mr. Weed has devoted much time to their study, embodying the results of his investigations in the present paper. He presents most forcible reasons for dividing the great thickness of beds which have heretofore been included in the Laramie into two distinct horizons, restricting the use of the term "Laramie" to the sandstones conformable to the underlying marine Cretaceous, and designating the overlying unconformable beds as "the Livingston formation." The physical conditions shown in the Yellowstone valley are strikingly in accord with those described by Mr. Cross along the Front range in Colorado. It is by such detailed studies that we shall finally arrive at the true geological limits of the Laramie formation.

In the accompanying paper Mr. Knowlton admirably supplements the work of Mr. Weed. He discusses the fossil flora from both horizons in the Yellowstone valley, reviewing all the material obtained since 1871. The two papers taken together form an important contribution to our knowledge of these beds.

I take pleasure in recommending its publication as a Bulletin of the U. S. Geological Survey.

Yours, very respectfully,

ARNOLD HAGUE,
Geologist in Charge.

Hon. J. W. POWELL,
Director U. S. Geological Survey.

OUTLINE OF PAPER.

Briefly summarized, this paper gives an account of a series of beds heretofore embraced within the Laramie, and covering the greater part of the state of Montana east of the Rocky mountains. It is shown that the thickness of some 13,000 feet of sandstone shales and conglomerates belong to three formations: the Laramie, the overlying Livingston, and the higher Fort Union beds. The Laramie is briefly described, and an account given of the overlying series of strata composed of water-laid and assorted volcanic material, which are named the Livingston beds. Observations prove that these beds overlie the coal-bearing true Laramie rocks, and that they contain intercalated beds of true volcanic agglomerate. The entire Livingston formation is overlain by a great thickness of beds of fresh-water sandstones, of which the Crazy mountains are formed, which are believed to be of Fort Union age. Stratigraphical evidence is presented to show that the Livingston beds are of post-Laramie age, yet older than and distinct from the Fort Union Eocene. Evidence is given showing an uplift with erosion during the accumulation of the Livingston beds, and after the formation of the Laramie coal beds, and it is shown from the composition of the conglomerates and their relation to the consolidated ejectamenta of explosive volcanic eruptions and from the nature of the overlying beds forming the Crazy mountains, that we have undoubted proof of powerful dynamic movements, accompanied by an eruptive activity following soon after the epoch of the coal-bearing Laramie, and marking the inception of that long period of volcanic action which continued with various interruptions into Pleistocene times, and formed the great volcanic area of the Yellowstone National park.

THE LARAMIE AND THE OVERLYING LIVINGSTON FORMATION OF MONTANA.

By Walter Harvey Weed.

INTRODUCTION.

The region of the Great Plains which forms the eastern portion of Montana and the Cordilleran region of the western part of the state, present widely different types of scenery and geological structure. The first is but a continuation of the broad trans-Mississippian plains stretching northward along the eastern front of the Rocky mountains far into Canadian territory. The latter is a complex of mountain ranges, where the folding and faulting of the rocks is both intricate and obscure. It is with a portion of the border line between these two sharply contrasted regions that the present paper deals, a region where the slightly folded rocks of the plains are warped and crumpled upon the flanks of the mountains that form the easternmost portion of the Cordilleran area.

In the foothill country, lying at the base of the mountains south of the Yellowstone river, near Livingston, Montana, a series of water-laid strata, composed mainly of volcanic detritus and overlying the coal-bearing Laramie beds, was observed by the writer in 1890, while studying the geology of the region, in continuation of the work of the Yellowstone park survey. Further exploration proved that the series covers a large part of this region and is separable lithologically and by evidences of unconformity into a distinct formation.

Measured sections of the strata about the Crazy mountains show a thickness of 12,000 feet of fresh water sandstones and clays referred to the Laramie. It is now possible to subdivide this great thickness of beds into Laramie, a higher horizon herein named the Livingston, and the still higher beds of the Crazy mountains, which have not as yet been differentiated into horizons, but probably represent the Fort Union beds of eastern Montana.

These beds present proof of a series of events following the epoch of the coal-making Laramie similar to those described by Whitman Cross,[1]

[1] The Denver Tertiary Formation. Amer. Journ. Sci., vol. XXXVII, April, 1889. Post-Laramie Deposits of Colorado. Am. Jour. Sci., XLIV, July, 1892.

in Colorado, of which the Arapahoe and the Denver beds are the evidence. The importance of this post-Laramie elevation and erosion with accompanying volcanic activity has been strongly insisted upon by Mr. Emmons,[1] and is confirmed by rapidly accumulating evidence observed in different parts of Colorado.[2]

The strata described in the present paper, though differing in many points from those of Colorado, attest a somewhat similar period, and afford the first recognition of the epoch outside of Colorado.

In this part of Montana the orographic movements that produced the Rocky mountain ranges were accompanied by periods of volcanic activity prolonged into late Tertiary time, which resulted in the accumulation of vast quantities of agglomerates, breccia, and lava flows, out of which great mountain ranges have been carved. These volcanic accumulations have been studied for many years in the region of the Yellowstone park and the adjacent country, where they rest upon Archean gneisses, eroded Paleozoic limestones, and Cretaceous sandstone alike, but no definite age could be assigned to the beginning of this long period of disturbance and volcanic activity.

Examinations of the Laramie and post-Laramie strata east of Livingston showed that these beds were several thousand feet thick, and included an intercalation of volcanic agglomerate that represents, in part, the source of the sands and pebbles of the stratified rocks. As the water-laid beds of the series contain determinable plant remains and a scanty fresh-water fauna, they possess decided interest in the light they throw upon the age at which the remarkable series of volcanic eruptions of this region began.

GEOGRAPHY OF THE REGION.

The region in which these formations have thus far been mapped and studied embraces a part of the Rocky mountains and the country eastward. Geographically the region is an interesting one, embracing the headwaters of the Missouri river, and its great tributary, the Yellowstone. The country north of the Yellowstone National park, with that about the headwaters of the Missouri, is a mountainous tract, through which the Yellowstone and the three rivers that uniting form the Missouri, have cut valleys that divide this elevated area into north and south ranges, known as the Snowy mountains and the Gallatin, Madison, and Jefferson ranges. These mountains end abruptly northward in the Yellowstone and in the Three Forks valleys, but the front range of the Rocky mountains is continued north of the Gallatin range by the lesser uplift of the Bridger, which with the lower elevations of Sixteen-mile creek connect the southerly ranges with the Big Belt and Little Belt mountains. The Snowy mountains, which inclose the park

[1] *Bull.* Geol. Soc. Amer., vol. I, 1890, pp. 245–280.

[2] *R. C. Hills*, Proc. Col. Sci. Soc., 1890.

upon the north, are encircled by the Yellowstone river, whose broad valley about Livingston is typical of its further course.

North of the Yellowstone river are the Crazy mountains, a strikingly picturesque and rugged group of peaks. They form an isolated mountain mass standing out prominently by themselves, and separated by wide valleys from the front ranges of the Rockies that encircle them on three sides. In the Crazy mountains and the valleys between them and flanks of the adjacent ranges the formations herein described attain their most interesting development. The southernmost part of this region has been called the Bozeman coal field, as it is an area distinguished by the occurrence of the productive Coal-measures of the Laramie lying east of the city of Bozeman. The "field" is adjacent to the Northern Pacific railroad and is situated 50 miles north of the Montana boundary line, embracing the entire foothill country between the Yellowstone river and the mountains to the south, from Big Timber to Livingston, as well as the rugged country westward, forming the Missouri-Yellowstone divide and the foot slopes of the Bridger range. The mountains bounding the field upon the south are steep and rugged peaks belonging to the Snowy range, through which the larger streams have cut deep canyons on their way to the lower country of the plains. The largest of these streams is the Yellowstone river, which, after leaving the Yellowstone park, flows through a couple of picturesque mountain valleys and intervening canyons and emerges from the mountain region at Livingston. West of this point the railroad follows up a small stream to the Muir tunnel, which gives access to the Missouri drainage, the coal-bearing strata forming a belt south of the railroad as far as Rocky canyon, where they turn northward and are continued along the base of the Bridger mountains and the low uplifts that connect this range with the Little Belt mountains.

GENERAL GEOLOGY.

The structural features of the region present several peculiarities of interest. The mountains lying between the National Park and the Yellowstone river, known as the Snowy range, consist in the main of Archéan rocks and volcanic accumulations. The northern peaks of the range show Paleozoic rocks dipping steeply to the northward away from the Archean plateaus. The cànyons cut by the streams that issue from the mountains show an S-shaped fold parallel to the mountain front, and modified by a tendency to en échelon folding. Faulting of this fold has brought up Archean rocks, which form high and sharp peaks entirely surrounded by Paleozoic rocks. West of Livingston the warping takes the form of a succession of short anticlinal folds arranged en échelon, with a northeast trend, their axes dipping more or less steeply in the same direction. These folds end in the overturn forming Mount Ellis and the south end of the Bridger range. Nowhere is the relation between geologic structure and topographic relief more clearly shown, and the cutting across of the anticlinal folds by the mountain streams clearly reveals the details of their structure.

The Bridger range is a fold involving the Livingston and all earlier rocks, of which the eastern side alone now remains. The low mountains northward show parallel anticlinal folds, running north and south, broken through in the Elk mountains by an extensive intrusion of quartz porphyrite. In the extensive synclinal basin thus inclosed upon three sides by the uplifts of these front ranges of the Rocky mountains, the Crazy mountains, form a magnificent monument of erosion. The main mass of these mountains is formed by a synclinal of post-Laramie strata, in which the sedimentary rocks have been baked and metamorphosed about a great core of igneous rock, from which dikes radiate on every side.[1]

The geology of the Gallatin, Madison and Jefferson ranges, defined by the three forks of the Missouri, is discussed by Dr. A. C. Peale in the text of the Three Forks Atlas sheet of the U. S. Geological Survey.

A number of carefully measured sections were made at different localities, from a study of which and the review of the fossil remains thus far collected, the different terranes have been discriminated. The following section represents the entire stratigraphic series from Cambrian to post-Laramie as developed in the region under discussion.

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[1] Geology of the Crazy mountains, Montana, J. E. Wolff, Bull. Geol. Soc. Amer., vol. 3, pp. 445-452.

Geological series exposed near Livingston, Montana.

7,000		Livingston beds—sandstones, shales, and conglomerates.
4,700	1,000	Laramie coal-bearing sandstones and shales; leaf remains, and invertebrates.
	1,500	Montana—sandy shales and argillaceous shales.
	1,600	Colorado—argillaceous limestones, with bituminous shales at base.
	600	Dakota—sandstones and conglomerates.
460	-------	Jura { Sandstones. / Limestones and shales.
1,900	400	Carboniferous { Quartzites, sandstones, and interbedded limestones.
	1,500	Limestones, massive, fossiliferous.
450	250	Devonian { Limestones and shales.
	200	Limestones—very massive.
835	410	Cambrian { Limestones, generally massive, with limestone conglomerate, alternating with shales.
	425	Soft shales, with interbedded impure limestones and basal quartzite.
		Algonkian schists.

The section is well exposed in the canyon of the Yellowstone, 4 miles south of Livingston.

THE MESOZOIC SECTION.

A detailed section of the strata overlying the Jurassic limestones has already been published by the writer, but is republished herewith in greater detail, in order that the nature of the Laramie and its relations to the underlying Mesozoic and overlying Mission creek beds may be fully understood. It represents the series as exposed near the town of Cokedale, some 10 miles west of Livingston.

This section was measured on the slopes west of the south fork of Cokedale creek, and begins at the point where this stream cuts across the anticline of Canyon mountain and exposes the Jurassic shales and limestones.[1] A section of the strata in this vicinity was made for the Northern Transcontinental Survey, a graphic representation of which is published in the very interesting account of the Bozeman coal field written by Mr. G. H. Eldridge.[2]

Section at Cokedale, Montana.

		Chocolate conglomerate, 400′ above coal-seam horizon.
		Shaly beds; chocolate-colored.
Laramie.	30	Conglomerate—local and passing into sandstone; volcanic.
	2	Limestone.
	210	Sandstone, shaly.
	6	Coal (seam worked at Cokedale).
	112	Sandstones.
	20	Sandstone ledge; fissile; crest.
	575	Sandstone; thick beds alternating with thin seams of shale and coal.
	75	Bluff sandstones; massive, white, etc.
Montana.	150	Tombstone sandstones.
	1149	*f* shaly beds .... 175 *e* sandy shales; dark gray .... 245 *d* shales and thin layers of sandstone . 315 *c* shaly sandstone .... 40 *b* sandstone shale .... 112 *a* shale 262
	25	Sandstone, forming crest ledge of 2′–6′ (25′ near creek); very prominent; pitted, and outcrops marked by pines.
Colorado.	300	Shaly beds, weathering down to brown earth with intercalated sandstones. { *e* shales 195; *d* sandstone 3; *c* shales 50; *b* sandstone 2; *a* shales 40 }
	30	Sandstone; big ledge, but not showing on summit of hill; conglomerate at top.
	350	Shales; gray; sandy.
	7	Yellow sandstone, fine-grained and fissile, forming striking topographical feature of this depression.
	247	Shales marked by sharply cut gully.
	12	Sandstone ledge; gray, very fissile; massive crop, and not generally a ledge.
	217	Shales.
	10	Sandstone; micaceous; fucoid impressions; forms low hogback ridge.
	455	Shales.
Dakota.	60	Quartzite; supposed to be summit of Dakota.
	40	Sandstones; fissile and slabby.
	200	Red or yellow limestone or sandstone, with pebbles.
	8	Quartzite.
	10	Lilac limestone, magnesian, becoming pebbly at base; passing above into red clays.
	25	Dakota conglomerate; forming hogback.
Jurassic.	105	Shales; dark gray; crumbly and earthy.
	50	Sandstones; indurated, slabby, cross-bedded; white quartz grains, and rusty cement.
	60	No exposure.
	5	Sandstone; fissile and crumbly.
	70	Red shale.
	5	Dark-gray shale.
	40	Limestones, forming lenses in sandstone grit or conglomerate, both carrying broken fossils.
	75	Sandstones.
	200	Myacites beds.
	75	Quartzite; Carboniferous.

JURA.

The base of this section is the belt of impure limestone and shale that overlies the heavy bed of quartzite capping the Carboniferous. These Jurassic limestones and shales contain an abundance of fossils, among

[1] Bull. Geol. Soc. Amer., vol. II, pp. 349–364.

[2] *Reports, Tenth* Census U. S., vol. XV, Mining Industry, p. 739.

which Gryphea and Myacites are the most plentiful. The rocks are soft shales or impure limestones, readily weathering down so that the beds most frequently form a gulch parallel to the strike, where monoclinal folding prevails. Overlying these beds the strata are sandy, and grade into a coarse crystalline limestone full of fossil fragments and changing rapidly into a very remarkable cross-bedded grit, frequently conglomeratic. This bed has been recognized over large areas of central Montana and is generally a conspicuous ledge outcropping on the slope beneath the Dakota "hogback." The fossils found in it are largely fragmentary, but show *Gryphea*, *Ostrea stringulata*, *Camptonectes pertenuistriatus*, and *Rhynconella myrani* in abundance. Between this bed and the Dakota conglomerate there is a series of shaly beds in which no fossils have been found, alternating with sandy strata possessing no marked characteristics. Both sandstones and shales are seldom exposed, but form the slopes between Jura and Dakota ledges. These beds have in the section been assigned to the Jurassic. They correspond in stratigraphic position and lithological character to the fresh-water Jura of Colorado, are variegated in color, but in the absence of fossils can not be positively assigned to the Jura.

CRETACEOUS.

The Dakota.—The Dakota forms the most persistent and readily recognizable horizon of the Rocky mountain Mesozoic. In this region it is generally a sandstone usually with a characteristic conglomerate at the base, which, with the associated sandstones, resists weathering and in the upturned strata of the foothills stands out very prominently. This conglomerate is overlain by variegated magnesian limestone, carrying pebbles at the base, and of a prevailing lilac or red tint. These beds grade into soft sandstones succeeded by sandy shales, and these by a thin bed of fine-grained dark-gray limestone, full of gasteropod shells. An examination of these fossils by Dr. C. A. White, together with the stratigraphical position of this limestone, shows it to be equivalent to the fossiliferous Dakota beds of Bear river, recently described by Mr. T. W. Stanton. This is overlain by sandy shales with some carbonaceous markings (but no recognizable plant remains), capped by the dense pink and white finely granular sandstone or quartzite that is assumed to be the top of the Dakota. It is a very hard rock, resists erosion well, but breaks into great cubical blocks, whose débris is abundant on the slopes and in the valley drift.

Colorado group.—Overlying the beds referred to the Dakota there is a great thickness of shales, with interbedded sandstones. The lower part of this series consists of rather dark carbonaceous shales, with lighter arenaceous beds and occasionally sandstones. In their sandy nature and the presence of beds of sandstone, the beds show evidence of the proximity of a shore line. Fossils obtained from these beds by

W. M. Davis prove the Colorado age of the strata. The following species were identified by R. P. Whitfield:

Inoceramus umbonatus M.
problematicus M.
sp?
undabundris M.
Ostrea congesta.
Gryphea vesicularis.
Exogyra.
Gyrodes depressa M.
Pholadomya Berthoudi (probably *P. papyraceæ*).
Several other species that appear to have no taxonomic value were also found.

Montana group.—A satisfactory discrimination between the beds of the Colorado and those forming this group can not be made on paleontological grounds, as few fossils have been collected in the beds assigned to the Montana. The lower thousand feet consists of sandy shales, impure limestones, and occasional thin sandstones, the whole becoming more arenaceous towards the top and grading into thinly bedded sandstones. These latter beds sometimes form bluff exposures, but more often weather out in "tombstone ledges." In the eastern part of the field the dark gray sandy shales are directly overlain by a heavy ledge, of yellow, rather dark, and very massive sandstone, which is thought to be the equivalent of the Fox hills. It is immediately overlain by the whiter, cross-bedded, and somewhat softer massive beds of the Laramie Coal-measures. No fossils have been obtained from this supposed Fox hill sandstone, which may prove to belong to the Laramie.

Those irregular and local elevations of the Cretaceous sea bed that occurred in the region east of the mountains in Canada and northern Montana, and resulted in the accumulation of estuarine and lacustrine deposits, known as the Belly river beds, are not indicated in the rocks of this vicinity. The Montana beds indicate a varying subsidence and the proximity of a low land mass with a gradual shallowing of the waters that resulted in the accumulation of the sandstones and coal seams of the Laramie.

THE LARAMIE FORMATION.

The Laramie, the chief coal-bearing formation of the Rocky mountain region, is well developed in Montana. In the particular area under discussion the strata form a continuous belt stretching westward along the flanks of the Snowy mountains, and northward upon the slopes of the Bridger and Little Belt ranges. Isolated exposures also occur in the mountainous region to the west, which though of small geographical extent, present structural features of much interest.

The area in which the Laramie strata are exposed is the region adjacent to Livingston is shown upon the geological map, Plate I.

The rocks of this formation form a group which is sharply defined both by fossils and physical characters. The beds consist of massive light-colored sandstones, with intercalated shale beds and coal seams near the base, becoming less frequent toward the top. The lower delimitation of the Laramie is assumed to be the dark and heavy bed of massive sandstone, assigned to the Fox hills, found below the lowest workable coal seam and resting directly upon the readily distinguishable and lithologically distinct gray shales and fissile argillaceous sandstones of the Montana group. The upper limit of the Laramie in the region studied is marked by an abrupt change in the composition of the beds and closely resembles in general characteristics that change which has been found so prominently developed in Colorado.

This definition of the Laramie is in accord with the original definition of King, and conforms to the usage of Newberry, Emmons, and Cross, though differing from the limits assigned on theoretical grounds by Prof. White, which are based upon faunal characteristics. The occurrence of marine Cretaceous fossils in the Laramie, showing temporary recurrence of salt-water conditions following a considerable period of coal-making depositions is now a well-established fact.

As exposed at various localities throughout this region the average thickness is 1,000 feet. This is exceeded in the hills north of the Bridger mountains, but is about the thickness throughout the Bozeman coal field. The exposures can not be directly compared, however, since there is proof of a considerable period of erosion following the deposition of the beds of the Laramie group, during which the upper portion of the series may have been in part removed, before the deposition of the Livingston. The sandstones which form the characteristic feature of the group and distinguish it from the underlying formations occur in beds of varying thickness, alternating with gray shales carrying plant remains, and seams of coal. The thicker beds of sandstone are generally massive, but the rocks have a laminated structure, following the cross bedding, and erode into picturesque bluff faces. The shales and coal seams, abundant near the base, become less frequent higher in the series, though a workable coal seam is generally found near the top of the series as exposed throughout the Bozeman field. These coal seams form a prominent feature of the series, and though but three or four of the many seams are of workable thickness and purity, have given an economic importance to the formation that has stimulated exploration and added much to our knowledge of the areas covered by this formation.

In general these coals are valuable fuels, differing materially from the lignites of the plains to the east, and are in ready demand throughout the state. They are mined at a number of localities throughout the Bozeman coal field, but elsewhere in this part of the state have not been commercially developed.

The following section is typical of the lower part of the Laramie throughout this region:

Section of Laramie Coal-measures at the Bowers mine.

Number of bed.	Thickness in feet.	
28	30	Massive sandrock, firm, light gray.
27	½	Coal seam.
26	10	Sandstone, breaking into small angular fragments.
25	1	Shale, dark gray.
24	6	Coal seam.
23	12	Shale, hard and slaty.
22	10	Sandstone, with shelly structure.
21	3	Coal; middle seam.
20	6	Red limestone, very magnesian.
19	3	Sandstone.
18	¾	Coal; called by the miners "upper bastard vein."
17	30	Sandstone, thinly fissile, brown.
16	¾	Coal.
15	10	Sandstone, shaly at top.
14	4	Coal.
13	20	Fissile and leafy sandstone.
12	30	Sandstone, massive, with jointed surfaces rounded.
11	6	Coal; poorly defined; vein 2 or 3 feet; the rest shale.
10	15	Sandstone, massive, brown, much pitted by weathering.
9	2	Coal.
8	3	Sandstone.
7	8	Coal and slate.
6	3	Sandstone, very fissile and soft.
5	10	Sandstone, hard and firm.
4	1½	Coal.
3	3	Shale.
2	18	Sandrock.
1	2	Coal.

The general characters of the formation are very constant in this particular region—though there is a decreasing amount of coal as the strata are followed northward to the Musselshell river, or into the plains region east of the Crazy mountains.

The lithological characters of these Laramie sandstones present few points of especial interest by themselves, but are of importance when compared with those of the overlying formations. The rocks are rarely compacted, or so firmly cemented as to form quartzites; in thin sections they are seen to be typical sandstones, formed mainly of well-rounded grains of quartz, with mica and accessory minerals, all indicating the erosion of Archean rocks. No fragments or minerals of an eruptive nature are found in any of the sections so far examined. No vertebrate remains have been discovered in the Laramie strata of this particular part of Montana. Leaf remains occur abundantly in the shales overlying many of the coal seams, but the rocks are so crumbly and the specimens so difficult of preservation, that few have been brought in. Leaf remains rarely occur in the sandstones.

The perfect stratigraphic continuity of the marine Cretaceous with the Laramie is apparent everywhere. No break occurs and no evidences of unconformity have been observed, up to the top of the formation. The evidences of such a break and unconformity between this and the overlying Livingston formation are given in the description of those beds.

In the clay shales associated with the productive coal seams, Unio remains have been found, the specimens being too poorly preserved for specific determination, and *Corbula subtrigonalis* M. and H. has been identified for me by Dr. White. Fossil plant remains are not uncommon in these shale beds, but the material is too soft to bear transportation, and only a few forms have been brought in. They are discussed at length in Prof. Knowlton's report.

THE LIVINGSTON FORMATION.

Overlying the coal-bearing Laramie strata, there is a series of beds constituting a newly recognized formation, for which the name Livingston is proposed, as it is typically developed in the vicinity of Livingston, Montana. The formation consists of a series of beds, in places aggregating 7,000 feet in thickness, composed of sandstones, grits, conglomerates, and clays, made up very largely of the debris of andesitic lavas, and other volcanic rocks, and including local intercalations of volcanic agglomerates.

DISTRIBUTION.

The accompanying map, Plate I, shows the surface distribution of the Livingston beds in the country about Livingston, the map representing part of the geological atlas sheet bearing that name. The formation attains its greatest development in this region, and in the country immediately north of the area shown by the map—that is, in the region east of the Rocky mountains. But exposures also occur within the mountain region, in the Madison and Jefferson ranges, where they have been mapped and described by Dr. A. C. Peale and indicated upon the Three Forks atlas sheet, and the region drained by Sixteen mile creek, north of the Bridger range, contains a considerable area of these beds. In the Crazy mountains the Livingston is covered by the Fort Union strata, which in this part of the field everywhere overlie and conceal the earlier deposits.

Although the origin of the formation is such that it varies greatly at different localities so that horizons can not be closely defined, there are three general divisions into which the formation may be separated, viz: The leaf beds, the conglomerates, and the volcanic agglomerates. The first two comprise the lower and upper parts of the formation. The third is an intercalation of volcanic ejectamenta that only occurs locally, though attaining a thickness of 2,000 feet in the southeastern part of the region covered by the Livingston beds. The total thickness of the formation approximates 7,000 feet in the region east of the mountains, where the agglomerates are absent. Of this total thickness from 600 to 2,000 feet may be assigned to the lower division.

THE LEAF BEDS.

The strata grouped together under this name embrace the basal portion of the formation up to a point where a decided change in color, mechanical constitution, and general nature appears, and includes the various horizons in which plant remains have thus far been found. A definite upper limitation is not always possible. On the flanks of the Snowy range the intercalated agglomerates form a convenient point at which to draw the line. Elsewhere it is marked by light colored, thinly bedded sandstones, with green or purple shales, which are readily distinguishable in the field, and are arbitrarily assumed to be the base of the conglomerate series.

This lower division of the Livingston deserves a somewhat detailed description, because it is the only portion yielding paleontological remains, and presents, moreover, features of lithological character and mechanical constitution separating it from the Laramie strata that so generally underlie it. The character of these lower beds, as exposed throughout this region is, therefore, quite fully described. In general it consists of a series of sandstones, conglomerates, and shales composed largely of angular or but slightly water-worn débris of volcanic eruptions and ash showers, that rest directly upon the productive Coal-measures. Usually the beds are dark colored and weather into ledges whose appearance suggests a volcanic rock, often breaking down into fine angular débris, forming slopes that support a scanty vegetation. Consisting mainly of sandstone, grits, and conglomerates, the beds vary in coarseness at different localities. Contrasted with the Coal-measure sandstones beneath, the rocks are darker, much harder, well indurated, brittle, and break into fine angular bits, while the Coal-measure sandstones are fissile, light colored, and often crumble into sand on weathering. Their intimate composition presents a striking difference in the nature of the two formations, the Laramie sands being well rounded quartz grains derived from Archean land areas, the materials being well assorted and stratified; the Livingston rocks, on the contrary, being composed of angular or slightly water-worn grains, showing no assorting of the material and consisting mainly of andesitic fragments cemented by fine volcanic ash. Plant remains are abundant at various horizons. The thickness of the leaf beds varies greatly at different localities; it is least in the eastern part of the field and increases westward, reaching a thickness of over 2,000 feet in the vicinity of the Muir tunnel and in the range of hills east of the Bridger mountains.

In the foot slopes of the Snowy range these leaf beds are generally green in color and differ somewhat in character from the beds belonging to this horizon in other localities.

THE BLUE RIM SECTION.

A fine exposure of the lower horizon is seen in the canyon walls of the west Boulder river in the extreme eastern part of the region shown in the map (Pl. I). The rocks occupy a shallow synclinal trough capping gray Cretaceous sandstones, and form picturesque cliffs locally known as the Blue rim. A few miles above these cliffs the river emerges from a canyon with walls of gneiss 2,000 feet high, at the northern end of which the section of upturned Paleozoic rocks is well exposed, and the succession of beds from the base of the Cambrian to the rocks of the Blue rim is clearly revealed.

The following detailed section of the beds is introduced to show the variations of the strata:

Blue rim section.

29. Sandstones of varying nature, color, weathering, and fracture, but of substantially the same rock. Occasional pebbles, but not assorted nor arranged. Cross bedding rare. Lense bedding occasional. In general, the arrangement and appearance of the strata is similar to that of the Yellowstone tuff beds of the Fossil Forest. Jasperized wood occurs, but the trees are prostrate.
28. Sandstone, fine grained, and breaking into slabs.
27. 6′. Shale? a dark brown ferruginous belt, that is unusually persistent.
26. 2′. Shaly rock, crumbly, earthy brown, not unlike ordinary Cretaceous shales.
25. 8′. Tuff-sandstone, very fine grained and green colored.
24. 6′. Sandstone or ash bed; forms lowest ledge of cliff.
23. 20′. Sandstone, gray and breaking into small fragments.
22. 3′. Sandstone, massive, weathering like a Laramie ledge.
21. 30′. Shaly bed, fissile and shaly, dark ferruginous, with carbonaceous material staining surfaces,
20. 1′. Sandstone, rather gray and micaceous.
19. 8′. Shaly sandstone.
18. 3′. Sandstone jointed, gray, hard, and indurated.
17. 25′. Shaly beds, crumbly brown bed, covered by slide of ledge above.
16. 12′. Sandstone, forming persistent ledge, well jointed, very hard, and holding lenses of brown cemented rock in lower part.
15. 1′. Green ledge of crumbly rock.
14. 9′. Shaly rock.
13. 6′. Sandstone, massive.
12. 5′. Shaly brown beds.
11. 3′. Sandstone, massive gray, cross bedded, thickens to north and thins out to south.
10. 12′. Splintery shale, greenish brown.
9. 3′. Sandstone, massive.
8. 8′. Shale, splintery, crumbly, green micaceous.
7. 2′. Limestone, dark blue.
6. 5′. Crumbly brown shale.
5. 3′. Gray sandstone.
4. 5′. Sandstone, green earthy, fracturing.
3. 30′. Massive sandstone, probably Laramie.
2. 20′. Shale, dark gray, carbonaceous, with thin layers of sandstone.
1. 50′. Massive sandstone.

The Blue rim section shows beds of water-laid sandstones and shales at the base, while the sandstone forming the blue cliffs are made of volcanic detritus, the finer-grained rock and the shaly beds being of volcanic ash and showing but little assorting. Plant impressions occur near the top of the section and prostrate tree trunks of silicified wood are seen. The shale belts are peculiarly inconstant, and the brown color is the result of the oxidation of the fine-grained green rocks.

An examination of thin sections of the rocks of the Blue rim section under the microscope, made by Mr. J. P. Iddings, show that the sandstones at the base consist of well-rounded grains of Archean material, mainly quartz, well assorted and quite like the sandstones of the Laramie Coal-measures of other places. Fifty feet above the basal sandstones the rock shows, in thin section, decidedly angular grains of plagioclase, quartz and a little mica, and though but one fragment of andesite is seen in the slide the rock has more the appearance of a volcanic ash than a true sandstone. Still higher in the section the sandstone (No. 16) is formed of rounded grains of Archean material, but above this the rocks show in thin sections a decidedly volcanic nature, consisting of fine fragments of pyroxene andesite and andesitic breccia. The shaly strata are formed of so fine an ash that but little can be distinguished in thin section, but they grade into the coarser beds whose composition is clearly volcanic.

DISTRIBUTION AND CHARACTER.

Followed westward the beds of the Blue rim increase in thickness and include more water-worn material, the tuff beds becoming less prominent. The rocks form picturesque combs along the valley of Little Mission creek and are well exposed where the Blue Rim syncline is cut across by Mission creek above the forks. At this place the rocks consist of brownish ash beds overlain by green fissile sandstones and conglomerates. In the walls of McAdow canyon of the Yellowstone the beds are well exposed and their relation to the coal rocks clearly seen. At this locality the shaly beds are often quite carbonaceous and contain an abundance of plant remains and a few fresh-water shells.

At Livingston fine exposures of the formation occur in the hills north of the town, where the beds dip at 10° northward. The rocks are dark chocolate colored or green sandstones, carrying lenses of fine grained tuff-like rocks, that contain plant remains. Local beds of volcanic débris, showing little if any water-assorting, also occur. In the sag between the two hill tops, an opening has been made on a two-foot seam of impure lignite, overlaid by a thickness of several hundred feet of sandstones that are locally conglomeratic.

A detailed section of the beds of the Livingston formation at Cokedale would be of little value, as the beds vary rapidly from quite fine-*grained* sandstones to coarse grit, with thin intercalations of conglomerate. Thin sections of the rocks, when seen under the microscope, show a variation in the amount of Archean material present. The rocks immediately overlying the coal are good sandstones, harder than those associated with the coal, but water-laid and formed of assorted waterworn grains. The rocks above change rapidly, however, to coarse-grained sandstones of angular fragments, showing but little assortment. Many of the rocks resemble a fine-grained volcanic agglomerate in the hand specimen, while the finer layers that crumble into small angular bits are volcanic ash beds. There is a noticeable admixture of Archean detritus with the volcanic grains of some of the ledges, but the latter largely predominate and frequently form the entire rock. At some 2,300 feet above the coal the Archean material is very abundant, showing a cessation of the ash showers, but the grits above and those associated with the shales of the Billman creek valley are wholly of volcanic material.

In the exposures of Rocky canyon and vicinity, from which the larger part of the plant remains obtained from the Livingston beds have been taken, the rocks immediately overlying the workable coal seam at the top of the Laramie are dark green or brown and resemble fine volcanic tuffs made up of andesitic débris, overlaid by grits and sandstones, with conglomerate intercalations, at 400 feet above the coal. Leaf remains occur at various horizons, but the collections all come from the lower 500 feet of the formation.

Upon the eastern flanks of the Bridger range, and northward to the Castle mountains, the leaf beds possess the same general characters. Hard sandstones of varying texture and grain, generally dark colored, and rarely conglomeratic, alternate with dark olive brown shales, that are hard and indurated, but crumble into fine angular bits. The conglomerates are composed almost wholly of pebbles of andesitic materials, but pebbles of white, brown, and blue quartzite occur sparingly, together with rounded fragments of coal and normal sandstones. Intercalations of volcanic agglomerate occur on the slopes of the Bridger range at Flathead pass, and farther north, about the headwaters of the Musselshell.

Fine exposures of this lower division of the Livingston occur in the hills drained by Cottonwood creek, where they rest upon the Laramie. The lowest beds are seal brown, very fine-grained sandstones, containing fossil plant remains in abundance, overlaid by coarser, lighter-colored sandstones and grits, which at higher horizons are interbedded with soft shales. In the exposures at the head ot Smith river, near Castle, a few gasteropod shells and Unio remains were found in the finer-grained beds. In this vicinity the first marked change is observed in the beds. Throughout the region north of the Crazy mountains a prominent bed of white calcareous sandstone occurs, interbedded with the dark colored sandstones, grits, and shale beds of the Livingston, about 500 feet above the base. No fossils were observed in this rock in the vicinity of Castle, but near the forks of the Musselshell river this bed is composed of brackish-water shells of Laramie types. The northern portion of the Crazy mountains is composed very largely of Livingston rocks. A section made along Lebo creek east of the mountains showed a total thickness of 7,100 feet of Livingston sediments, in which the lower beds do not form so distinct a division as elsewhere in the neighborhood of the Crazy mountains.

In the mountainous region south of the Gallatin valley the only exposure of the Livingston is in the Madison range, where the beds cover an area of 15 to 20 square miles in the vicinity of Sphinx mountain. They are thus described by Dr. A. C. Peale: "The strata consist of indistinctly bedded volcanic material, mostly andesitic in nature, and of a somber hue. At one or two places conglomerates made up of all sorts of pebbles are seen near the base." The beds rest unconformably upon the eroded edges of all the Cretaceous formations, and are unconformably overlain by the coarse conglomerates assigned to the Eocene. On the eastern flanks of the Jefferson range another exposure of the Livingston occurs. The beds present a somewhat different aspect from those just described, not being so dark in color and showing more distinct evidences of bedding and seemingly more nearly conformable to the underlying Laramie beds with which they are in contact. In the vicinity of the Jefferson canyon they have a dark greenish-gray color, and apparently contain interbedded hornblende andesites, which seem to have been laid down as lava flows. Other beds are conglomerates composed of all sorts of volcanic material, andesites, however, as at other localities, apparently predominating. The period during which they were deposited was undoubtedly one of great volcanic activity.

The water-laid beds of the basal portion of the formation thus far described contain but small and local bodies of conglomerate. In the section which has already been given, made in the vicinity of Cokedale, these beds have been estimated to be 2,400 feet thick. In the Blue Rim section, which does not embrace the entire thickness, there is some 600 feet, and on the Bowlder river, where they are capped by the volcanic agglomerate, the total thickness is not thought to exceed some 700 feet.

THE VOLCANIC AGGLOMERATES.

Beds of consolidated volcanic ejectamenta form the mountains of the western part of the Crow Indian reservation and terminate the Bozeman coal field at the Boulder river. These agglomerate beds rest directly upon the lower beds of the Livingston formation, and thinning out westward are overlain by the upper part of the same formation, capped in turn by the great thickness of sandstones and clays forming the Crazy mountains.

The volcanic agglomerate attains its maximum development in the region drained by the Boulder river. This stream is a clear mountain torrent, heading in the high plateaus and peaks north of the Yellowstone park, and emptying into the Yellowstone river at Big Timber. In its lower course below the forks the valley is cut in the volcanic agglomerates, which weather into castellated knobs and mural faces, adding much to the picturesqueness of the scenery. At the forks of the stream the Laramie Coal Measures dipping northward are overlain by the dark-colored rocks of the Livingston formation, readily distinguishable by their color, fracture, and weathering. The upper parts of this section are cross bedded, poorly assorted sandstones, very clearly of shallow water formation. The grains are angular, but little water worn, though not less so than the rocks of the Blue Rim. A careful examination shows at a number of localities a decided unconformity between the beds at the top of the series and the overlying agglomerates. At other localites there is an apparent gradation of the water-laid strata into the fine breccias, so that the section shows distinctly water-laid beds capped by a series of strata in which those beds alternate with beds showing no traces of such action. The latter become more frequent in ascending the series until the rocks are all fine-grained breccias that pass rapidly into the coarse volcanic agglomerates made up of large angular fragments of andesitic lavas. The agglomerate beds are very light colored, possessing in a general view a warm gray tint. The fragments composing them are of various tints of gray, brown, lilac or green, the last color often predominating. There is a rude bedding brought out by the rapid weathering of fine-grained material forming thin intercalations rarely more than a few inches thick. The agglomerate fragments range in size from minute particles up to blocks four feet in diameter, though seldom so large as the latter. The lavas from which the agglomerates are formed are all andesitic, the rocks possessing but slight variations in character. Augite-andesite is often conspicuous, the large augite phenocrysts being very abundant. In several large blocks of basic-looking andesite large isolated hornblende prisms were noticed. As a whole the rocks though so light colored, are decidedly basic and in thin section are seen to be pyroxene-andesite.

These agglomerates represent the products of explosive volcanic action from a vent on the shore or in the shallow water of the lake whose sediments formed the Livingston beds. The flanks of the cone built up of this volcanic débris were covered by the lake waters in the subsidence that caused the deposition of the great thickness of sandstones and clays that form the Crazy mountains.

DISTRIBUTION.

In the valley of the lower course of the Boulder river the total thickness of agglomerate interbedded between the Livingston rocks is estimated to be at least 2,000 feet. The beds dip at a low angle downstream and are seen to be overlain by sandstones and purple clays a few miles above Big Timber, frequent sections being exposed in lateral stream cuttings

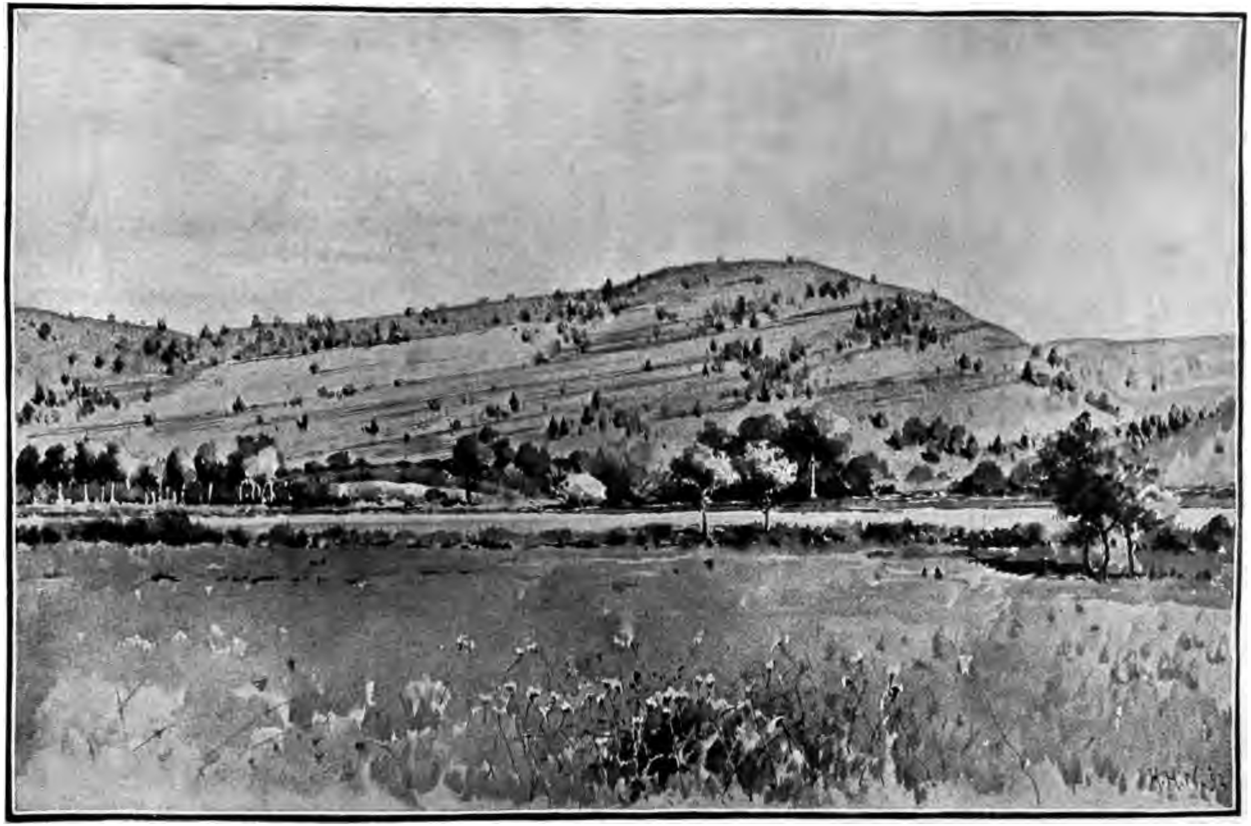
East of the Boulder river these agglomerates form the highly accidented country of the Crow reservation, where they rest upon upturned and eroded Mesozoic rocks. In this region a thickness of over 2,000 feet was observed in a canyon where the underlying rocks were not exposed to view. A portion of this breccia is, however, believed to represent subaerial accumulations deposited contemporaneously with the water-laid strata that cover the agglomerates near Big Timber.

Followed westward from the Boulder river the agglomerates are exposed as far as McAdow canyon and Hunter's hot springs. In the hilly country between the Boulder and Yellowstone rivers the agglomerates are of little moment in the topography; gentle grassy slopes fall off gradually to the broad cobble-covered terrace flats that border the Yellowstone river. In this region exposures must be sought in the rocky walls of the little canyons cut by the branching headwaters of Mendenhall and Antelope creeks. These exposures show a gradual thinning out of the agglomerates to the north.

In the bold bluffs facing the river near Springdale, a railroad station 25 miles east of Livingston, the rocks dip at an angle of 15° eastward, showing the influence of the McAdow canyon folding. The Springdale bluff shows a thickness of about 700 feet of breccia, resting upon typical Livingston beds and covered by the purple clays and lilac sandstones that prevail eastward. The cliffs are some 200 feet high, formed of light-colored agglomerates that, when seen at a little distance, closely resemble ordinary sandstone. The base of the section consists of dark tufaceous sandstones resting upon the water-laid beds of the Livingston series. The lowest ledge of the Springdale bluff is a very hard and dense, almost black, sandstone, very brittle, and breaking into angular débris. It is immediately overlain by a ledge locally characteristic of the base of the breccia. This rock is full of dark brown, round concretions, 1 to 2 feet in diameter, that resemble cannon balls. The "cannon ball" bed is overlaid by beds of fine volcanic material resembling a coarse and poorly assorted volcanic ash showing no evidence of water action. These ash beds are in turn overlain by a second cannon-ball ledge in which the concretions are much smaller. Above this last bed fine-grained agglomerates and very coarse agglomerates alternate in rapid succession and without persistence of horizon. The fragments composing these agglomerates of the Springdale block are andesitic lavas identical with those forming the beds of the Boulder river; green, brown, lilac and gray in color and varying in size from fine lapilli to blocks of 5 feet across (see Pl. II).

In the bluffs of Mendenhall creek east of Springdale station the same rocks are exposed underlain by the cannon-ball beds and resting upon the earthy brown and splintery shales and sandstones of the Livingston series. East of Mendenhall creek the agglomerates are covered by the overlying sandstones.

The most northern exposure of the agglomerates yet found is near



TILTED AGGLOMERATE BEDS NEAR SPRINGDALE, MONTANA.

that local health resort, Hunter's hot springs, some 3 miles north of the Yellowstone river. In this interval the agglomerates thin out rapidly, and in the section exposed by the creek a mile west of the hot springs, just south of the wagon road, the conglomerate is but 25 feet thick and rests unconformably upon the sandstones beneath. The upper surface is uneven and covered by the lilac sandstones and purple shales that usually are above it. (See fig. 1.) There is a general de-

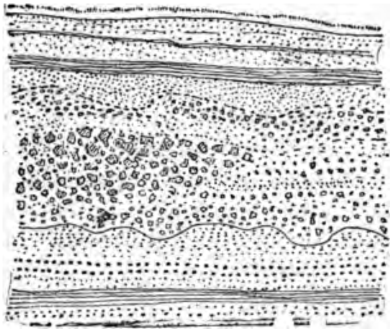


FIG. 1.—Diagrammatic section at Hunter's Hot Springs.

crease in the size of the fragments, as well as the thickness of the beds, from the Boulder river northward. In the area thus far mapped and studied the volcanic agglomerates cover about 75 square miles. They also extend over a larger area in the western portion of the Crow Indian reservation.

Small and local intercalations of volcanic ejectamenta showing no assortment or rounding by the action of water, occur, however, at a number of localities in the lower part of the Livingston formation. Such accumulations are prominent in the vicinity of Flathead pass, and at the head of Smith river, near the mining camp of Castle. The beds exposed east of the Crazy mountains frequently consist of finer grained material, which, in thin section under the microscope, is seen to be a good pyroclastic rock. The areas of Livingston rocks in the Madison range and along the Jefferson river, described by Dr. A. C. Peale, also consist in part of true volcanic accumulations, the latter exposure showing interbedded lava flows.

RELATIONS TO LEAF BEDS.

A gradual increase in the thickness of the beds is noted in tracing the thinning out of the agglomerates, and the thickness at Cokedale corresponds approximately to that of both the agglomerates and underlying beds together of the eastern localities. It is supposed that in a general way the deposition of the subaerial agglomerates was synchro. nous with the formation of littoral deposits of débris washed down from the slopes of the neighboring volcano, making beds of a somewhat higher horizon than those beneath the agglomerate. At the same time there was a shore to the westward supplying Archean débris which mixed with volcanic particles appears in increasing quantity as the rocks are followed westward from the Boulder.

LIVINGSTON CONGLOMERATES.

The upper portion of the Livingston is for convenience designated by this name, as the conglomerates form the most important and often the most conspicuous beds of this part of the formation.

Overlying the leaf beds and volcanic agglomerates there is a series of shales and interbedded sandstones and grits that form a prominent part of the formation wherever the upper portion is exposed. In the eastern part of the region the sandstones are fine and uniform in grain, making an excellent building stone in the vicinity of Big Timber. Traced westward these beds are easily recognized by their red soils that form the terrace flats to the south of the Yellowstone river as far as Springdale. Beyond here they form the low hills and the country north of Livingston. It is in these same shales that the valley of Billman creek has been cut, and they have also afforded the material out of which the long strike valley east of the Bridger mountains has been eroded. In the extension of these beds westward there is a general persistence of character of the shales themselves, but on the other hand the thin beds of "freestone" of the east change in character, become coarser, and in the Billman creek valley form lenticular bodies of coarse and illy assorted grits and conglomerates. Northward the open valley of Flathead creek and the synclinal basin north of the Shields river valley are both eroded in this part of the Livingston formation. The exact nature of the soft clayey shales it is difficult to make out; they crumble readily, are sometimes quite micaceous, and change from green to red on weathering. Thin sections of the associated sandstones show them to be made of volcanic material, grains of andesitic breccia forming a considerable part of the mass. This series of beds has thus far failed to yield any fossil remains.

Overlying the series of purple shales just described, the rocks are chiefly sandstones and conglomerates. They do not form a distinct conglomerate bed throughout the field, but rather a series of sandstones and silty shales holding intercalated beds of conglomerate, the latter rocks becoming more prominent toward the west, and attaining their maximum and most prominent development along the eastern front of the Bridger range. That they form a true part of the series is indicated by their composition and by the gradual transition of the underlying beds into the conglomerate series. Because of their coarser nature a study of the pebbles is more easily made in these beds, and this has been most feasible in the exposures of the western part of the field.

Near Hunter's hot springs the monoclinal ridges back of the hotel *are formed of* sandstones belonging to this horizon that include lentic-

CONGLOMERATE BEDS FORMING ANTICLINAL RIDGE BETWEEN BRACKETT AND FLATHEAD CREEKS.

ular intercalations of conglomerate, in which, besides the usual variety of volcanic rocks, gneiss, quartzite and limestone pebbles were recognized. These ledges are overlain by sandstones and purple clays that represent the higher part of the formation. At the mouth of Shields river the sandstones interbedded with the purple and green clays are dark and greenish in color and contain conglomerate layers with quartzite and limestone pebbles.

From Big Timber westward the grains forming these rocks become very slightly coarser and in the high hills east of the Bridger range become conglomerates. These hills are separated from the mountains by a long strike valley cut in the purple shales and drained by Bridger and Brackett creeks. The cliffs east of these creeks show a thickness of over 2,000 feet of sandstones, conglomerates, and sandy shale. Several detailed sections were made, but are of little general interest, save to show the proportion of conglomerate. Brown earthy-colored sandstones grade rapidly into conglomerates and alternate with gray, silty, incoherent clay-shales. The rugged ridge separating Brackett creek from the flat valley to the north is formed by a sharp anticlinal uplift of these conglomerates. Plate III shows the ledges on the summit of the ridge. The importance which attaches to these conglomerates arises from the light they throw upon the relation of the Livingston formation to the Laramie, and to the post-Laramie movements which elsewhere had been found to be so important. The large size of the pebbles of the conglomerate permits a ready recognition of their lithological nature, and this upon examination proves to be of the greatest interest. In the cliffs east of Bridger creek and the ridges cut by Brackett creek, the conglomerates of the series occupy a very prominent part of the formation. The accompanying illustration (Pl. IV) shows the size and well-rounded character of the pebbles forming the conglomerates. It is reproduced from a photograph. Sections made near Stone's creek and on Brackett creek show a thickness of 2,000 feet of very coarse sandstones and conglomerates in which a large number of pebbles are noted that are not of volcanic origin. In both these sections the conglomerates contain pebbles of granite, quartzite of various colors, limestones showing chert and carboniferous fossils, and cretaceous shales and sandstones. The volcanic rocks also show a wide variety; whereas the pebbles of the lower beds show but little variety of the andesite, those of the higher strata exposed at Bridger and Brackett creeks contain olivine porphyrite, hornblende-porphyrite, pyroxene-andesite, quartz diorite, and dacite. The first of these rocks is unknown elsewhere in this region. The dacite occurs as an intrusion in the Laramie Coal-measures.

There is some evidence that may prove sufficient cause for a separation of these conglomerates and silts from the Livingston formation and their recognition as the base of the Fort Union group.

MATERIALS COMPOSING THE LIVINGSTON.

The peculiar appearance of the rocks overlying the coal beds of the Bozeman coal field was noticed by the geologists of the Hayden Survey,[1] but the volcanic nature of the pebbles was first established by the geologist belonging to the Northern Transcontinental Survey, by whom descriptions of the conglomerates were published.[2]

The general appearance of the coarse sandstones of the lower part of the formation suggests the volcanic nature of the materials composing them. In the hand specimen particles of andesite are frequently distinguishable, and the opaque white feldspars derived from the andesites are always a conspicuous feature of the rocks. The conglomerates of the leaf beds, though always of merely local development, are frequently prominent parts of the outcrop. The pebbles of these conglomerates are almost wholly andesitic in character, the rare exceptions being a few pebbles of quartzite found at a few localities at this horizon.

Microscopic examinations of the rocks show a mixture of volcanic with archean material. The character of the rocks of the Blue rim section has already been stated. That of the strata in the vicinity of Cokedale is typical of this formation generally. The lower 1,000 feet of beds show an admixture of andesitic débris with Archean material, the latter being much more abundant than in the rocks of the Blue rim, but in widely varying quantity at different horizons. Many of the Cokedale rocks show no assortment of the grains, as there would be if there had been wave action during their deposition, and they probably represent ash showers. The andesites are all of types represented by the intercalated volcanic agglomerates, described later. Thin sections kindly examined for me by Mr. Whitman Cross show the rocks overlying the coal near the Chestnut mine to be composed of fine to coarse andesitic débris but little different from that seen in thin sections of rocks from the same horizon north of the Crazy mountains.

The conglomerates of the upper part of the formation show a much wider variety in composition. Inconspicuous features in the exposures east of Livingston, they form the high hills east of the Bridger range, where they attain their greatest development and become less and less prominent parts of the formation northward. In the hills just mentioned the conglomerates consist of well-rounded pebbles up to 10 inches in diameter, which, though chiefly of volcanic rocks, are of many types, and include moreover a conspicuous proportion of other rocks. Microscopical examinations show the following variety of igneous rocks:

Olivine-porphyrite.
Hornblende-porphyrite.
Pyroxene-andesite.
Quartz-diorite.
Dacite (or rhyolite?).

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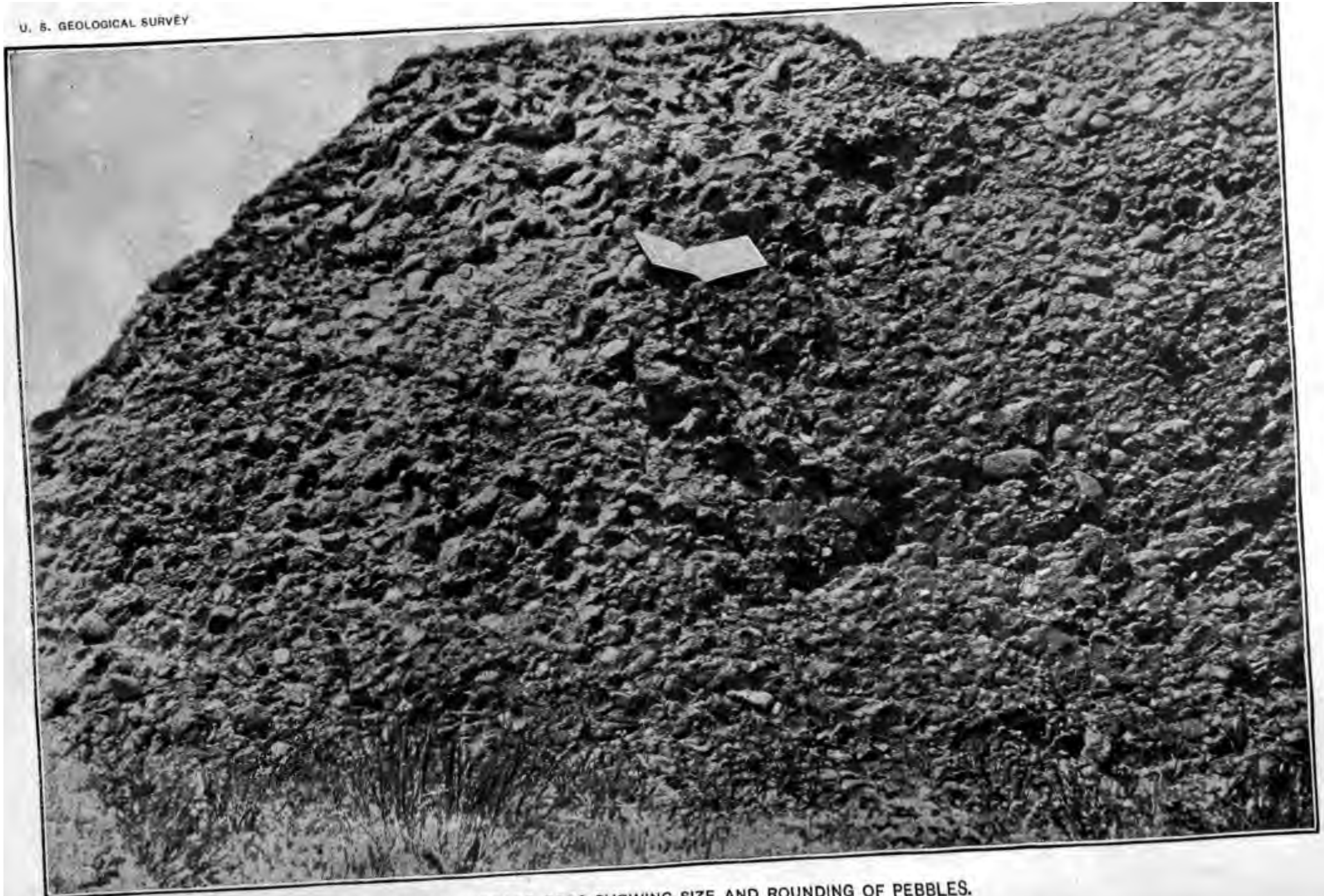
[1] Dr. A. C. Peale, Ann. Rept. U. S. Geol. and Geog. Survey, 1871, pp. 49, 173; idem, *1872, pp. 25, 112.*

[2] *Waldemar Lindgren,* vol. xv, Tenth Census U. S., p. 725.



CONGLOMERATE BEDS SHOWING SIZE AND ROUNDING OF PEBBLES.

Pebbles of Archean, gneisses, and quartzites also occur, together with limestones showing Paleozoic fossils and Dakota conglomerate.

FOSSIL REMAINS OF LIVINGSTON FORMATION.

The fossils of the Livingston formation consist of plant remains, found most abundantly in the southern exposures, throughout the Bozeman coal field, and a meager molluscan fauna most abundant in the extreme northern portion of the Crazy mountain country.

FOSSIL FAUNA OF THE LIVINGSTON.

The molluscan remains are of two kinds, fresh-water and brackish-water forms. The former occurs together with leaf remains in the cliffs of McAdow canyon of the Yellowstone and at the headwaters of Smith river. At the first locality *Unio* remains, specifically indeterminable, and fragmentary gastropods have been collected. At the head of the south fork of Smith river a small collection of fossils was obtained from the black calcareous shales of the formation, but the shells have been deformed by the flexing of the strata. Unio remains are abundant, but can not be preserved. The other shells brought are abundant and have been examined for me by Mr. T. W. Stanton, who reports as follows: "The fosssils from this locality are very imperfectly preserved and the identifications are too doubtful to be of value. All that can be said of them is that they are fresh-water forms having some resemblance to species from the Fort Union bed near Fort Union and at the mouth of the Yellowstone, as follows:

1. *Goniabasis tenuicarinatu* M and H.
2. *Goniabasis nebrascensis* M and H.
3. A third form represented by a single mold resembles *Thaumastus limnæiformis* M and H, a land shell."

In the region northeast of the Crazy mountains, drained by the Musselshell river, a bed of limestone full of shell remains occurs, interbedded with the Livingston sandstones and conglomerates, a few hundred feet above the base of the formation. The species obtained from this bed, are thus described by Mr. Stanton: "The three species and one variety in this lot are all brackish-water forms, and were all originally described from the Judith river beds near the mouth of Judith river. The Corbicula and the Corbula have been found in the Laramie of the valley of Bitter creek, southern Wyoming, and the Corbula ranges well down in the marine Cretaceous. There is no doubt that these fossils came from the Laramie.

1. *Ostrea subtrigonalis* M. and H.
2. *Corbicula cytheriformis* M. and H.
3. *Corbula subtrigonalis* M. and H.
4. *Corbula subtrigonalis*, var. *perundata*, M. and H.

The horizon from which these brackish-water forms were obtained is below that at which the fresh-water mollusks were found

FOSSIL FLORA OF THE LIVINGSTON FORMATION.

The abundance of fossil plant remains in both the true Laramie and the Mission creek formations has already been noted. Collections were made from both horizons as early as 1871 by Dr. A. C. Peale and other members of the Hayden Survey, and together with further collections made in 1872 and 1878 were submitted to Prof. Leo Lesquereux. In subsequent years the collections were largely increased by Dr. Peale, Prof. F. H. Knowlton, and the writer. At my request a careful revision of this work, together with a study of all other material from the same region, was undertaken by Prof. Knowlton, and his report is a very important contribution to the paleobotany of the Laramie. This work not only describes and tabulates the species collected from the Laramie Coal-measures and those from the Livingston formation, but it clears up the confusion resulting from the mixing up of collections from various horizons and localities described in the early reports of the Hayden Survey, a work so frequently referred to in the literature of the Laramie. As many of Lesquereux's type species of Laramie plants were in these collections, the importance of a careful separation of collections from different localities and horizons will be readily appreciated. This necessitated a careful examination of each specimen of the Hayden collections. This has been done by Dr. A. C. Peale, by whom most of the specimens were obtained. This has shown that fossil plant remains from both the Laramie Coal-measures and the Livingston formation were placed together, and with specimens from the volcanic rocks of the Yellowstone park were described as Laramie species. The latter have been separated out and the specimens from each locality and horizon in the Bozeman district discriminated. The collections studied by Prof. Knowlton are from five different localities and represent two horizons, viz, first, Laramie Coal-measures, and, second, the Mission creek formation. The first includes the specimens labeled Bear creek, Fir canyon, and Fort Ellis, Chestnut and the Craig and Horr mines (Cinnabar field). The specimens labeled Hodgson coal mine, Flathead pass, Mission creek and Bear creek (Madison valley) are from the lower portion of the Livingston formation, and can be readily distinguished by their volcanic matrix from the specimens obtained from the Laramie rocks.

In the accompanying report Prof. Knowlton has shown the similarity of the flora of the Livingston beds with that of the Denver formation, and the table of distribution and the relative abundance of certain species show quite clearly that the flora of the Livingston is distinct both from that of the Laramie and that of the Fort Union formation.

UNCONFORMITY BETWEEN LARAMIE AND LIVINGSTON FORMATIONS.

Unconformity between these two formations has been observed by Dr. A. C. Peale in the vicinity of Sphinx mountain in the Madison range. At this place an area of Livingston beds, representing the lower part of the formation, rests in marked angular unconformity upon the Dakota, and all later formations including the Laramie. An uplift, followed by an erosion of about 3,000 feet of strata at the close of the Laramie and before the deposition of the Livingston, is quite clearly evidenced. Throughout the region east of the mountains examined by the writer, the Livingston beds have not been found resting upon strata older than the Laramie. Considerable variations in the thickness of the latter are believed, however, to be in part due to a period of erosion preceding the deposition of the Laramie.

Undoubted proof of unconformity between the two formations is, however, afforded by the pebbles of the conglomerates of the Livingston. The Cretaceous section up to and including the Laramie affords proof of considerable oscillation of sea and land, but there is good ground for believing that the earlier sediments of this age were nowhere elevated and subject to erosion. The sandstone and conglomerates of the Laramie all indicate their derivation from Archean land. No fragments of other rocks have yet been observed. In the Livingston, on the contrary, there are pebbles from all earlier rock masses, indicating very clearly the erosion of adjacent land masses consisting in part of upturned sedimentary rocks and forming the record of a period of erosion of 6,000 feet or more of strata. The conglomerates contain pebbles referable by fossils or lithological peculiarities to the Laramie, Montana, Colorado, Dakota, Jurassic, and Carboniferous, together with others of limestone that may be Cambrian, and a variety of quartzites and gneisses that are probably Archean. This lithological proof of a great unconformity is in itself a sufficient cause to disregard the apparent conformity of the two formations in the region east of the uplifts of the Front ranges. It is evident moreover that the slight erosion of this region, and the horizontal attitude of the strata during the erosion interval, would necessarily make an unconformity less marked and much harder to detect in this region than nearer the shore line where the coarser sediments and the greater uplift and erosion all reduce the unconformity more apparent.

THE FORT UNION FORMATION.

In the Crazy mountains and the broken plains country to the east the Livingston is overlaid by a series of beds, believed to be a distinct formation, corresponding in stratigraphic position and fossil contents to the beds exposed along the Missouri river at the mouth of the Yellowstone, so long known in geological literature as the Fort Union beds. A detailed description of this formation will not be given here, as it will be discussed in another paper. The formation consists of rather massive, cross-bedded sandstones, with gray, silty shales and local lenses of impure limestone. In lithological habit and general field appearance the formation is easily distinguished from either the Laramie or Livingston rocks, and its fossil contents consist wholly of land and of fresh-water mollusks, and of plants characteristic of the Fort Union of the Missouri river. A measured thickness of 4,000 feet was observed overlying the Livingston, on Labor creek east of the Crazy mountains. The rocks of this formation have never been found west of the foothills of the Rocky mountains, but cover the greater part of the plains to the eastward.

AGE OF THE LIVINGSTON FORMATION.

The different views held by geologists upon the age and relations of the Laramie group, are due to a fundamental difference in the definition. The name was originally applied by King to the series of conformable sediments ending the marine Cretaceous.[1]

A very much wider significance was given to the term Laramie by Dr. White, who correlated the various lignite-bearing strata of the Rocky mountain region, under the name Laramie group. Thus defined the name included formations which further researches show to be distinct in both stratigraphic relations and paleontological remains.[2] It is evident also that collections of fossils from this heterogeneous group of strata, having been described as from the Laramie group, have made the so-called Laramie flora and fauna an unreliable criterion, by which to distinguish true Laramie from post-Laramie strata.

The facts of stratigraphy and of lithology herein presented demand the recognition of the importance of the interval between the Laramie and the Livingston deposits. The importance of this interval is also shown by the plant remains of the two formations, which present such differences and biological development as fully sustain the deductions from stratigraphical evidences. It should be stated, however, that it is only now, since the thorough revision of the flora of the so-called Laramie, in which the collections from the Denver and the Fort Union have been separated, that such evidence is of value.

Unfortunately, the known molluscan remains do not aid us in determining the importance of this erosion interval, because the invertebrate fauna of the Laramie is as much in need of revision as the fossil flora. It has been repeatedly stated, by eminent paleontologists, that sedimentation has been continuous and uninterrupted from the beginning of the Laramie to the end of the beds called Fort Union, which are, in this paper, separated from the Livingston as a higher series. The fossil fauna has been said to be the same from base to top throughout this series. A careful tabulation of species from different horizons shows, however, that this is not true in the collections made from the vicinity of the Crazy mountains.

The oyster bed, found in the Livingston, clearly shows an interval of

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[1] Rep. Fortieth, Par. Survey, vol. I, p. 331.

[2] The Denver Tertiary Formation; Am. Jour. Sci., April, 1889. Post-Laramie Deposit of Colorado; Am. Jour. Sci., July, 1892.

quiet, succeeding the formation of the sandstones and grits of volcanic material, during which the beds were covered by brackish waters.

The fresh-water invertebrate fossils, at higher horizons, seemingly indicate a change in the character of the waters, and the final recession of the sea. The fossils of the oyster bed are, however, indentical with forms characteristic of the Coal-measures of the Laramie, underlying the Livingston in this same region, and therefore they can not be used as an argument for the separation of the two formations, but clearly show the existence of a Laramie fauna in brackish waters, after the deposition of several hundred feet of Livingston beds. It should be stated, however, that none of the conglomerates of the formation, in the region in which the oyster bed is found, contain pebbles indicating unconformity. It is indeed possible that these beds are incorrectly assigned to the Livingston, and should be classed as Laramie.

As the stratigraphical evidence herein presented shows an uplift, followed by a period of erosion after the deposition of the Laramie Coal-measures, and before the Livingston period, and the plant remains show a flora distinct from the Laramie flora, and allied to that of the Denver beds of Colorado, the Livingston beds are clearly to be assigned to the post-Laramie.

The facts discovered make it necessary to limit the use of the term Laramie to the original definition, which applied the name to the strata ending the sequence of conformable sediments of Cretaceous age; this leaves no alternative but to call the Livingston beds post-Laramie. Such a designation will, of course, be questioned by those using the term Laramie in a broader sense. The great thickness of beds overlying the Livingston formation, aggregating some 8,000 feet of strata and forming the Crazy mountains, has thus far proved too barren in fossils to assign positively any definite age to the strata. Upon lithological grounds and from its stratigraphical position it is regarded as an equivalent of the Fort Union strata of eastern Montana. This is supported by the leaf remains obtained from the beds.

CANADIAN NOMENCLATURE.

In the northward extension of the Great Plains and the foothills of the Rocky mountains into Canadian territory, the careful work of the geologists of the Canadian Geological Survey has added much to our knowledge of the Cretaceous terranes. Both Dr. Dawson and Mr. Tyrrell have subdivided the great thickness of strata found overlying the Montana group into series stratigraphically distinct. Though the term Laramie group is retained for the entire thickness, Tyrrell states clearly that the lower of the two series into which he divides the strata (*i. e.*, the Edmonton beds) is alone entitled to that name. The overlying Paskapoo series he considers distinct, and though there is no apparent break or unconformity between them and the Edmonton, the flora and fauna indicate an Eocene age. These beds are probably identical with the Fort Union group of Montana.

The Edmonton is described by Tyrrell as the most characteristic series of the Northwest territory, for although its thickness never exceeds 700 feet the strata are horizontal and overlie a great extent of country. They consist of whitish or light gray clays and soft clayey sandstones weathering rapidly and into rounded outcrops. The beds are frequently seamed with layers of ironstone whose nodules cap pinnacles cut in the soft sandrock. It is essentially a coal horizon and of considerable economic importance. The fossil fauna and flora includes a number of brackish-water shells, and dinosaurian remains and plant remains closely related to the Belly river, and of unquestioned Laramie types.

The Paskapoo beds include all the rocks generally ascribed in this part of Canada to the Laramie that overlie the Edmonton series. A thickness of 5,700 feet is exposed on the outer edges of the foothills. The rocks are light gray or yellow sandstones weathering brown, thickly bedded and cross bedded with light blue gray or olive sandy shales, holding intercalations of hard lamellar sandstones, and rarely lenses of blue concentric weathering limestones. The whole series is characterized by the presence of land and fresh-water shells, and a flora of Fort Union type.

Mr. Tyrrell says the Rocky mountain uplift began after the deposition of the Edmonton Laramie, the plains gradually sinking beneath the level of the fresh-water lake. The distinction between the Fort Union and the coal-bearing Laramie has been strongly insisted upon by Newberry, by whom the Fort Union with its wholly distinct flora was regarded as Eocene. That no unconformity has been recognized between the two in the region of the Great Plains is to be expected, but the collections of Prof. L. F. Ward from near Glendive, on the lower Yellowstone river, seem to show the absence of the Laramie as defined in this paper at that locality, the Fort Union resting directly upon Fox hill strata. The interpolation of the Livingston series and the great unconformity it shows, between the coal-bearing Laramie and the Fort Union, seems to be good and sufficient grounds for the adoption of Prof. Newberry's divisions, and places us in accord with the results of recent work in Colorado, so fully described by Cross and Hill in their recent publication.

POST-LARAMIE VOLCANIC ERUPTIONS.

The rocks described as parts of the Livingston formation all suggest the importance and extent of the volcanic activity that followed the coal-making period of the Laramie. The water-laid sediments and the terrestrial accummulations of breccias and agglomerate both clearly show the proximity of volcanic centers. These rocks have now been identified over parts of a large area of the Rocky mountain front in Montana and show that the eruptions were not merely local in character. At only one locality, observed by Dr. A. C. Peale, near the Jefferson river, have interbedded lava flows been observed. The deposits generally seem to indicate a period of volcanic outbursts, rather than profound intrusions or extensive outflows of later ages. This volcanic activity became the most important feature of Tertiary time in this region and profoundly modified the topography, which is today largely due to the breccias and lavas of that age. The importance of the Livingston rocks is apparent when it is considered that the volcanoes of that period were the ancestors of the great volcanoes of Tertiary time, and the definite establishment of the stratigraphical position of the earliest records of this activity is the foundation for the study of the order of succession of the volcanic rocks of the region and the geological history which they record.

It may be of interest in this connection to refer briefly to other occurrences of volcanic rocks in the Cretaceous. The presence of conglomerates formed of volcanic pebbles in what is here designated the Livingston series was noted by Lindgren while studying the relations of the coal beds to the older rocks for the Northern Transcontinental Survey.[1] In his later paper on eruptive rocks from Montana,[2] he states: "The character of the subaerial masses accompanying these eruptions is not well known; only a few conglomerates in the Laramie give some hint as to their nature. In the case of a volcanic conglomerate at the coal fields of Bozeman, the horizon could be determined to be 2,200 feet above strata in which fossils of the Fort Benton group were found. This conglomerate consists of pebbles of hornblende-andesite, to which consequently no later age than lower Laramie can be assigned."

In a conglomerate about 1,000 feet above Cretaceous No. 2, in the Highwood mountains, dacites and andesites were found by the same observer. Augite-andesite pebbles form a conglomerate exposed on Sixteen-mile creek, and considered by Lindgren to be Laramie.

In Canada Dr. Dawson has described the occurrence of volcanic agglomerates similar to those of Montana interbedded in a series of strata overlying the Kootanie coal seams, and referred to the Dakota. These agglomerates occur at a horizon about 3,350 feet above the Kootanie coal seams, and consist of "volcanic rocks chiefly, if not entirely, fragmental, forming an agglomerate of varying coarseness, frequently so fine as to be designated a volcanic ash." For the most part they are grayish green or purple, and toward the base weather easily, forming rounded crumbling masses. This description is equally applicable to the agglomerates of the Bozeman coal field. In the general geology of his report, Dr. Dawson alludes still further to the volcanic agglomerates: "The volcanic ash beds and agglomerates of the Cretaceous in this region are evidently due to a local eruption which had its center in the latitude of the Crow Nest pass. These volcanic rocks have, however, been traced north and south from this point over

[1] Tenth Census, vol. XV, p. 725.

[2] Proc. Cala. Acad. Sci., ser. 2, vol. III, p. 51.

a total length of 45 miles, and may probably have at one time had as great an extension east and west, though this has subsequently been diminished by the folding together of the beds. The volume of strata between the coal-bearing horizon and the base of the volcanic rock is estimated approximately at 3,350 feet in the Crow Nest pass, and 2,400 feet on South Kootanie pass. The volcanic rocks themselves are 2,200 feet thick at Crow Nest pass and thin rapidly to the north and south. Dakota plants are found a few hundred feet below these volcanic rocks."

SUMMARY.

The facts presented in this paper are believed to be an important contribution to our knowledge of the orographic and structural geology of the Rocky mountains. The post-Laramie movements that formed so important a part of the mountain building period in Colorado are herein shown to have this parallel in Montana and to accord with the observations made in Canada by Dawson and Tyrrell.

The facts which have been presented may be summarized as follows:

First. The coal-bearing Laramie terminated the succession of conformable cretaceous sediments.

Second. The beds overlying the Laramie Coal-measures give evidence in their pebbles of an unconformity with them and are distinguished by a remarkable change in their composition. To this series of beds the name Livingston formation is applied. It consists of sandstones, conglomerates, and shales, formed chiefly of andesitic volcanic material, with an admixture of Archean débris near the shore line. The beds show very little assorting by water action, the fragments are angular, and the lower part of the series is decidedly tufaceous, being frequently a fine volcanic agglomerate. These beds are consolidated, water-laid sediments formed of cinders, lapilli, and other ejectamenta of explosive volcanic eruptions. This material fell directly into the lake waters or was washed into them from the slopes of the volcano. The abundant plant remains of this formation are discussed at length in Prof. Knowlton's report.

Third. Volcanic agglomerates are intercalated in the Livingston formation. They are unmistakably subaerial deposits of coarse volcanic ejectamenta, compactly cemented by fine-grained ash and rudely bedded. They represent the material forming the flanks of a post-Laramie volcano, whose northern base was subsequently covered by the waters of a lake whose sediments form the rocks of the Crazy mountains.

The lower division of the Livingston beds is thinnest on the Boulder river, where the agglomerates are thickest, increases in thickness as the latter thins out, and attains a maxium development on the Missouri-Yellowstone divide, where the agglomerates are farthest away.

It is believed that the Livingston series and the volcanic agglomerates are the record of volcanic eruptions which began after the close of the coal-making Laramie and were attended by an uplift of considerable extent. Erosion of the volcanic slopes supplied the rounded pebbles and sands, while ash showers formed the coarser tufaceous rocks. In the eastern part of the Bozeman coal field the quantity of ejected material being greatest as nearer the source, the shallow waters were soon filled and the formation of the agglomerates began. Such gradual shallowing and filling are clearly indicated in the beds beneath the agglomerates. An examination of thin sections of the rocks forming the lower part of the Mission creek formation shows them to be composed of the same andesitic material as the agglomerates.

The rocks of this formation generally rest directly upon the Laramie Coal-measures in apparent conformity. The direct unconformity of the Livingston beds observed at Sphinx mountain and the positive proof of a great unconformity and subsequent erosion afforded by the composition of the conglomerates of the series show that the epoch of the coal-forming Laramie was terminated by an uplift of considerable extent. The land area resulting from this elevation was exposed to erosion during a prolonged period, in which a thickness of 4,600 feet of Mesozoic beds was removed and the Paleozoic limestones were exposed to denudation. The Livingston beds were deposited during this period of erosion. The lowest beds of the series in which no pebbles of sedimentary rocks have been detected may represent the area deposits following elevation. They certainly evidence a time of intense volcanic activity. The source of volcanic material is probably to be found in the volcanic outbursts of the Boulder river on the east and of the Flathead pass country to the north.

The recognition of the Fort Union formation above the Livingston is also believed to be an important discovery. This formation has long been a cause of controversy, and has by many been excluded from the Laramie. As its molluscan fauna is wholly fresh water, and, as such, is of little value in determining its age, the fossil flora has been relied upon for its discrimination, and this is clearly Eocene. The stratigrapic relations herein detailed seem to confirm this view.

ANNOTATED LIST OF THE FOSSIL PLANTS OF THE BOZEMAN, MONTANA, COAL FIELD, WITH TABLE OF DISTRIBUTION AND DESCRIPTION OF NEW SPECIES.

By F. H. Knowlton.

The first collection of fossil plants from what is now very generally known as the Bozeman coal field was made in 1871[1] by the members of Dr. F. V. Hayden's party while they were encamped at Fort Ellis, preparatory to beginning their memorable exploration of the Yellowstone national park. The actual collecting was done by Dr. A. C. Peale, Mr. Joseph Savage, and Mr. W. H. Holmes. The specimens, as I am informed by Dr. Peale, were all obtained on the same day and from the same vicinity, although not all at exactly the same spot. As the country was at that time new and unsettled, the nearest fixed point was the military reservation of Fort Ellis, and the specimens were labeled by the various collectors as follows: "Six miles above Spring canyon (now known as Rocky canyon), near Fort Ellis, Montana"; "above Spring canyon, near Fort Ellis," and "near Fort Ellis, above coal." The fact that there were three kinds of labels lead Prof. Lesquereux, to whom the specimens were submitted for examination, to suppose that they came from quite different localities, but in his published account[2] he referred them to the same horizon. Most of these specimens are fortunately still preserved in the collections of the U. S. National Museum, and it is therefore possible to correlate them with considerable certainty with the recent collections made in the same region.

The specimens of this first collection may be very readily separated into two groups by the character of the matrix in which they are preserved. The first consists of a very hard, dark metamorphic shale, breaking across the plane of stratification, and therefore rarely affording perfect impressions. The other is a lighter colored, but very coarse, hard sandstone not well suited for the preservation of the details of nervation.

The exact spot from which the original specimens in dark metamorphic shale were obtained has been revisited by Dr. Peale and myself

[1] Hayden's Ann. Rept., 1871, p. 296. [2] Hayden's Ann. Rept., 1872, p. 404.

and a considerable collection gathered, which contains nearly all of the species known, from a comparison of the types in the National Museum, to have come from there. It is the locality now known as Hodson's coal mine, and is on Meadow creek, about 12 miles southeast of Bozeman.

The precise point at which the specimens preserved in the coarse sandstone were obtained has not been rediscovered, as they were collected in 1871 by Messrs. Holmes and Savage, who have never revisited the place. There is, however, little reason to doubt but that it is the same horizon as that at which plants in exactly similar material have been obtained in recent years at the mouth of Bear canyon and near the mouth of Fir canyon. If this supposition be true, and there is no reason to suppose the contrary, as it can be traced continuously from the mouth of Bear canyon to the Meadow creek locality, this horizon is a little lower than the former or the one containing the dark cross-bedded shales.

Following is an enumeration of the material which has furnished the basis for the present paper, with a statement of localities and collectors:

The original collection of 1871, embracing forty specimens and twenty species preserved in the U. S. National Museum.

Timber line, Gallatin county, Montana. Collected by Dr. A. C. Peale, August 30 and and 31, 1883. A few nearly indeterminable fragments.

East side of Bridger range, 8 or 10 miles north of Bridger canyon, Gallatin county, Montana. Collected by Dr. A. C. Peale, August 9, 1885. Fragments determinable generically only.

East side of Bridger range, half mile north of Flathead pass, Gallatin county, Montana. Collected by Dr. A. C. Peale, August 28, 1885. Contains only three species.

Bear canyon, half mile above its mouth and 6 miles southeast of Bozeman, Gallatin county, Montana. Collected, August 25, 1886, by Dr. A. C. Peale. This is the coarse sandstone mentioned above and contains fragments of five or six species.

Near head of Fir canyon (north side), 8 miles east of Bozeman, Gallatin county, Montana. Collected by Dr. A. C. Peale, July 23, 1887, and September 28, 1888. Embraces about a dozen species.

Stone quarry on the road to Meadow creek and about half mile above its mouth. Collected by Dr. A. C. Peale and F. H. Knowlton, September 27, 1888.

Hodson's coal mine on Meadow creek, 12 miles southeast of Bozeman, Gallatin county, Montana. Collected by Dr. A. C. Peale, August 16, 1888, and by Dr. Peale and F. H. Knowlton September 28, 1888.

Mouth of Fir canyon, east side of East Gallatin river, 4 miles southeast of Bozeman, Gallatin county, Montana. Collected by F. H. Knowlton, July 3, 1888.

Between middle and north branches of Bear creek, east of Madison valley, on the east side of the Madison range. Collected by Dr. A. C. Peale August 20, 1889. This is really extralimital, but is included because it is the only other lot of plants from this part of Montana, and is moreover in material similar to that from Hodson's coal mine, and also contains some of the same species.

Horr and Craig mines, Cinnabar mountain, Montana. Collected by W. H. Weed July 17 and 18, 1890.

Near Little Mission creek and east of Mission creek. Collected by W. H. Weed, August 22, 1890.

ANNOTATED LIST OF SPECIES.

ANEMIA SUBCRETACEA (Sap.) Ett. and Gard.

Gymnogramma Haydenii Lx.

Only two or three small fragments observed.

ASPIDIUM LAKESII (Lx.) Kn.

Plate II, figs. 1–4.

Lathræa arguta Lx. Hayden's Annual Report, 1869, p. 96.

Sphenopteris eocenica Ett. Eoc. Fl. d. Mont. Prom., p. 9, Pl. II, figs. 5–8; Hayden's Annual Report, 1872, p. 376.

Sphenopteris Lakesii Lx. Tert. Fl., p. 49, pl. II, figs. 1, 1*a*.

Sphenopteris membranacea Lx. Hayden's Annual Report, 1873, p. 394; Tert. Fl., p. 50, pl. II, figs. 2, 2*a*, 3, 3*a*.

Habitat.—Between middle and north branches of Bear creek, east of Madison valley, on the west side of the Madison range, Montana. Collected by Dr. A. C. Peale August 20, 1889.

As stated in the list of localities this material is not from the Bozeman coal field proper, but is included on account of the fact that it is the only other lot of plants from this part of Montana, and moreover possesses exceptional biological interest. It is undoubtedly of same age as the Hodson's coal mine material. The form to which these specimens are referred occurs in great abundance in the Denver beds of Colorado and may be regarded as one of the most characteristic species of that formation. The collections from Colorado contain hundreds of specimens, but strangely enough not one has been found in fruit, and it is therefore of great interest to find the fruiting specimens and be able to settle definitely its systematic position. In absence of the fruit it was referred to the genus Sphenopteris by Lesquereux, but the fortunate finding of these fragments in fruit, as shown in Figs. 1, 2, 3, of Pl. VI, makes necessary their reference to the genus Aspidium.

The complete description of this species in the light of all known material is reserved for a subsequent publication, but in order to show that the Montana specimens agree in matter of outline and nervation with those from Colorado, a single specimen is figured (Pl. VI, Fig. 4) from near the Douglas coal mine at Sedalia, Colo.

EQUISETUM (?)

A minute fragment of doubtful identity.

ABIETITES DUBIUS Lx.

Lesquereux, Tert. Fl., p. 81, Pl. VII, Fig. 24; *non* Figs. 20, 21, 21*a*.

The specimens upon which this species was founded are preserved in the U. S. National Museum. After a careful study of them, together with all material since obtained from the same region, I have divided the species as defined by Lesquereux, a part going to *Sequoia Reichenbachi* Gein. (q. v.), and the small, rather doubtful remaining ones are retained under *A. dubius*.[1]

Abietites setiger Lx., described at the same time, is to be dropped. Schenck (Zittel's Handb. d. Pal., vol. II, p. 350) was the first to suggest that the fragment upon which this was founded was probably nothing but the roots of some plant, and an examination of the type specimens in the U. S. National Museum abundantly confirms this view.

SEQUOIA REICHENBACHI Gein.

Abietites dubius Lx., ex. p., Lesquereux, Tert. Fl., p. 81, pl. VI., figs. 20, 21, 21*a*.

Sequoia Reichenbachi is essentially a Cretaceous species and enjoys a very extensive vertical and areal distribution. It first appeared in the extreme upper Jurassic, is abundant in the Kootanie and Potomac formations and other lower and middle Cretaceous deposits, and is also found in the lower or true Laramie and the post-Laramie of Colorado and Montana.

The National Museum contains several specimens under this name from Spring canyon (Hodson's coal mine), although it does not appear in any of Lesquereux's publications, as found at this place. The recent collections also contain a number of fine specimens. They are distinguished from *Abietites dubius* Lx., by the smaller, more arched and very acute leaves, which were clearly sharply angled. I have referred here Figs. 20, 21, 21*a*, pl. VII, of Lesquereux's *Tertiary Flora*, there called *Abietites dubius*.

TAXODIUM DISTICHUM MIOCENUM Heer.

Heer, Mioc. Balt. Fl., p. 18, Pl. II; III, Figs. 6, 7; XIV, Figs. 24–28; XV, Fig. 1*a*; Flor. foss. arct., V, Pt. II, p. 33, Pl. VIII, Fig. 25*b*; IX, Fig. 1; Lesquereux, Tert. Fl., p. 73.

Taxodium dubium Heer. Lesquereux, Hayden's Annual Report, 1872, p. 389; 1873, p. 409.

Several specimens of this widely distributed species were found in the Hodson's coal mine material. One of them is a large, well preserved specimen, which makes the determination very satisfactory.

GINKGO ADIANTOIDES Ung.

Represented by several fine specimens.

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[1] For full discussion of the conifers of the Bozeman coal field, see forthcoming *Monograph on the Laramie* and allied formations, in preparation.

THINNFELDIA POLYMORPHA (Lx.) Kn.

Plate I, Figs. 1–4.

Salisburia polymorpha Lx. Am. Jour. Sci., 2d ser., vol. XXVII, 1859, p. 362; Hayden's Ann. Rept., 1872, p. 404; Tert. Fl., p. 84, Pl. LX, Figs. 40, 41; Knowlton, Proc. Biol. Soc. Wash., Vol. VII, p. 153.

Leaves cuneiform or long wedge-shaped, narrowed from above the middle downward into a strong thick petiole and rounded, erose or irregularly lobed or cut at apex; margin entire or more frequently strongly irregularly undulate or toothed; mid-vein very strong, continuing to the apex or in some cases nearly or quite vanishing just below the point; veins thin, close, simple, emerging at an acute angle from the mid-vein, thence running with slight curve to the margin.

The leaves of this species are very large, measuring in some instances fully 30^{cm} in length and $9–11^{cm}$ in width. The smallest specimen (Fig. 4), which may not be complete, is 10^{cm} in length by 3^{cm} in width, but most of the specimens, of which there are numerous fragments, are fully as large as the maximum size given above. They were provided with a strong thick petiole, as in Fig. 3, at least 3^{cm} long and 3^{mm} in diameter. In outline the leaves are long wedge-shaped at base, and rounded or variously, irregularly lacerate-toothed at the apex, as seen in Figs. 1 and 2. The margin, perhaps best seen in Fig. 2, is irregularly undulate, or in some cases, as in Fig. 4, slightly toothed. The mid-vein or rib is very thick and prominent, sometimes running clear to the apex, as in Figs. 2 and 4, while in others it vanishes just below the apex, as in Fig. 1. The lateral veins emerge at a very acute angle and are close, fine and only slightly curved in running to the border.

The name of *Salisburia polymorpha* was first given by Lesquereux[1] to some fragmentary specimens collected by Dr. John Evans at Nanaimo, Vancouver island. It was not described in this publication, the only statement being that, besides several species of dicotyledons, there was also "a very fine Salisburia, very variable in the outline of its leaves and named *Salisburia polymorpha* (Lesq.), distinctly related to *Salisburia adiantoides* (Ung.), found in the Pliocene of Italy." Lesquereux's next mention of this species was in Hayden's Sixth Annual Report (1872), when he identified as belonging to it certain fragmentary specimens obtained by Dr. A. C. Peale and Mr. Joseph Savage from "six miles above Spring canyon, near Fort Ellis, Montana," which locality is the same as that now known as Hodson's coal mine. He alludes to the Vancouver specimens, and states that they had been "described and figured for a final report, which was delivered to Dr. Evans but was never published." This report still remains, so far as known, unpublished, and therefore the Vancouver specimens are still without description or fig-

[1] Am. Jour. Sci., 1859, p. 362.

ures, existing only in name. The Spring canyon (or Hodson's coal mine) specimens were more fully described and illustrated, under the name of *Salisburia polymorpha*, by Prof. Lesquereux in his Tertiary Flora, where he states that he is not quite positive that they are actually the same as those from Vancouver, a view that, in the light of the present large series, is likely to prove correct. But in absence of either descriptions, drawings or specimens from Nanaimo, it is manifest, that according to the laws of nomenclature, the name must be permanently associated with the specimens first actually described, and it therefore falls to the Montana specimens. If subsequent investigation shows that the Nanaimo specimens are actually the same as those from Montana, they will of course take this name, but if they represent a good species of Salisburia (or Ginkgo) allied to *S. adiantoides*, as Lesquereux has said, they must receive a new name.

Some of the forms of this species seem at first sight strongly to resemble certain forms of Ginkgo, as Fig. 4, and in absence of a series for study Prof. Lesquereux was undoubtedly justified in supposing them to represent leaves of this genus. But when a considerable number of specimens are examined it is seen that they do not agree closely with Ginkgo, although it is possible that they are in some way connected with it. Four leaves of Ginkgo that have been identified as *G. adiantoides*, are found in beds of nearly the same horizon, but not actually associated in the same place. As these leaves can not be received in Ginkgo, I have thought best to place them under the somewhat miscellaneous genus of Thinnfeldia, which, according to recent views, seems best characterized to contain them. The genus Thinnfeldia should be placed according to the latest authorities among the conifers, a view which the present specimens undoubtedly confirm, but it has been shifted about from place to place. Thus Schenk at one time regarded it as belonging to the Cycadaceæ; while Saporta, Schimper, and at first Nathorst, would place it among the ferns, a position which some of the forms included under it would undoubtedly demand, for there are, judging from the published drawings, some true ferns. On the other hand, Ettingshausen and Nathorst, in his later views, would put this genus among the conifers, the former writer supposing it to be allied to the genus Phyllocladus.

The species under consideration is found in company with and is undoubtedly related to the following species, which in turn, is very closely related to *T. Lesquereuxiana* of Heer from the Atane beds of Greenland. Heer identified with his species Lesquereux's *Phyllocladus subintegrifolius* from the Dakota group of Kansas and placed it, under the heading *Incertæ sedis*, after the ferns. Whatever may be the disposition of the various species of Thinnfeldia, for this genus seems to be in need of revision, I am convinced that the Montana specimens under consideration belong to the conifers and are not far removed from the genus Phyllocladus.

Certain of the smaller fossil leaves, as Fig. 4, have a strong resemblance to certain living species of Phyllocladus, as for example *P. rhomboideus* Rich., from Tasmania, which is irregularly toothed or lobed on the margin but is larger and more regularly wedge-shaped at apex. The rachis is much the same in both. It is possible that it may be connected with other living species of Phyllocladus, but the limited herbarium at my command will not admit of further comparisons.

THINNFELDIA LANCEOLATA n. sp.

PLATE V, Fig. 5.

Leaves long-lanceolate, tapering gradually below into a thick petiole and above into a long, slender acuminate apex; margin entire or slightly undulate-crenate, especially above the middle; mid-vein very strong in the lower portion, gradually becoming thinner above and vanishing below the apex; veins numerous, close, simple or rarely forked; at an acute angle of divergence, running straight to the margin.

This species is well represented by the very perfect specimen figured (Pl. V, Fig. 5), as well as by several smaller less perfect fragments. It has a length of 31^{cm} and a width in the middle of 4^{cm}. The midrib at the base is very strong and thick and was evidently extended into a thick petiole, which is now broken. Another specimen of exactly the same shape is only about 25^{cm} long and 3^{cm} wide, but has neither the apex or base preserved. The midrib is very pronounced in the lower half of the leaf, but becomes gradually thinner until it vanishes in the upper fifth of the leaf. The nerves emerge from the midrib at a very acute angle. They are close, parallel and rarely, possibly never, forked.

This species is found associated in the same beds, and even on the same pieces of matrix, with the preceding, and is evidently closely related to it. The thick, prominent midrib and the numerous close veins emerging at an acute angle from it, are the same in both species, but the present species is readily distinguishable by its lanceolate form, with nearly entire margins and long acuminate apex. It is possible that they may represent leaves from different parts of the same tree, or of the same species under different circumstances, for as is well known, many living trees exhibit such striking differences in form and size of foliage as almost to preclude the probability of their belonging to the same species. But as both forms can be so readily separated by the characters pointed out above, and particularly as no intermediate forms have been detected, it is thought best, provisionally at least, to describe them as distinct.

The only described species of Thinnfeldia with which this form seems to be related is *T. Lesquereuxiana* Heer (Fl. foss. arct., VI, Abth. 2, p. 37, Pl. XLIV, Figs. 9, 10; XLVI, Figs. 1–12), with which Heer has also identified the *Phyllocladus subintegrifolius* of Lesquereux (Cret. Flora, p. 54, Pl. I, Fig. 12). It, however, differs by its much larger size and in being always pointed at apex and quite entire. It is not improbable, however, that they may be more closely related than the present specimens permit of deciding.

There are several living conifers with which this species is undoubtedly related, and were it not for the fact that it seems to be related to the preceding form (*T. polymorpha*), it might perhaps best be described under the name of the living genus. This living genus is Podocarpus, of the tribe Podocarpeæ. The species which it most resembles is *P. macrophylla* Wall., from tropical India, which has lanceolate leaves 6 to 8 inches in length and a little more than one-half inch in width, and of exactly the same shape as the fossil leaves. It has also a strong midvein with close, divergent, lateral veins, as in the fossil. *P. Rumphii*, from New Guinea, is also quite like the fossil species, as is *P. leptostachya* Bl., from Borneo, and *P. salicifolia*, from the island of St. Martha.

PHRAGMITES ALASKANA Heer.

The specimen referred by Lesquereux to this species is in the U. S. National Museum collection, and the newly obtained material agrees exactly with it.

CAULINITES SPARGANIOIDES Lx.

The fragments which Lesquereux had from this place were referred with considerable doubt to this species. The specimens in the latter collections are similar to those seen by Lesquereux, but the question as to whether they or any of them really represent the species under consideration is unsettled.

POPULUS MUTABILIS, var. ovalis Heer.

Not observed in the recent collections.

POPULUS LÆVIGATA Lx.

Only a single specimen, which is of the same character as that figured by Lesquereux from Rock creek, Laramie plains, being, however, much smaller.

POPULUS cf. ARCTICA Heer.

Plate II, Figs. 7–9.

Leaves broadly reniform with rounded lobes, a heart-shaped or slightly wedge-shaped base and very rounded apex; 5-nerved from the apex of the petiole, the nerves all of the same strength.

Habitat.—Near mouth of Bear canyon, 6 miles southeast of Bozeman, Montana. Dr. A. C. Peale, collector.

As will be seen from the figures the three leaves here referred provisionally to this species differ considerably among themselves, and there may possibly be two species, although probably not. Two of them

(Figs. 8, 9, of Pl. VI) are clearly similar. They have a very rounded outline, with a distinctly heart-shaped base. The five nerves, which are of nearly equal strength, all, or usually, arise from the apex of the petiole and do not arch much in passing to the borders. The other leaf (Fig. 7) has the same rounded outline, being as broad as or broader than long, but is wedge-shaped at base. The nerves are five in number, as in the others, and they diverge from the apex of the petiole in the same manner, but as the leaf is narrower the nerves have a more acute angle. In all the leaves it is a noticeable fact that the five nerves divide the leaf into approximately six equal parts, thus making a wider angle in the broad leaves than in the wedge-shaped one. The branching of the nerves, as far as it is possible to make it out, is the same in all. The further fact that they all occur at the same place and even on the same piece of matrix is suggestive of their belonging to the same species.

The question of their identity with *P. arctica* Heer is quite another thing. They can hardly be regarded as typical *P. arctica*, and yet they do not differ greatly from a few that have been figured as belonging to this species. Heer, Fl. foss. arct., Vol. I. Pl. V, Figs. 3, 4; Pl. XXI, Fig. 14; *op. cit.*, Vol. III. Mioc. Pfl. v. Grönl., Pl. II, Fig. 20*a*; *op. cit.*, vol. IV, Beiträge z. foss. Fl. Spitzb., Pl. XXXII, Fig. 3; Lesquereux, Tertiary Flora, Pl. XXIII, Figs. 1, 4, etc., while not absolutely similar, are very suggestive. In absence of sufficient material to make out a fuller description it has been thought best to leave them as above.

POPULUS? PROBLEMATICA n. sp.

Plate VI, Figs. 5, 6.

Fruiting ament long peduncled, the peduncle rather thick; capsules oblong, rounded at apex, pediceled.

Habitat.—Head of Fir canyon (north side) 8 miles east of Bozeman, Montana. Dr. A. C. Peale, collector.

The best preserved specimen (Pl. VI, Fig. 5), appears to have had a shorter peduncle than the other (Fig. 6), but it is partly obscured by the matrix and its full length can not be ascertained. The capsules at the base of this ament are long pediceled, but the pedicels become gradually shorter toward the apex of the ament and the capsules also become smaller. The other specimen (Fig. 6) is very obscure and the figure of it is in a measure conventional. It has a long, naked basal portion, and the capsules, if they be such, are more closely oppressed to the axis than in the best preserved specimen. It appears to have been in a younger state than the other at the time of its fossilization. It is also possible that it (Fig. 6) is not the same species as the other, for as remarked above, it is so obscure that it is made out with great difficulty.

It is with a good deal of hesitation that these aments are described under the name of Populus. As they occur at the same place, and one of them actually on the same stone with specimens of *Thinnfeldia polymorpha*, the first thought is that they represent fruiting aments of this species, a view further supported by the fact that no leaves of Populus have been detected in this bed. A careful consideration, however, fails to develop other than negative support for this theory, for the aments that have been described for similar forms differ widely. Thus the aments described as belonging to Ginkgo in the various volumes of Heer's Arctic Flora are entirely different. The nearest approach to it is *Czekanowskia setacea* Heer,[1] which has pediceled fruits not unlike Fig. 5. But the leaves of this genus, which have sometimes been found attached to branches bearing the fruits, are entirely different from anything that has ever been found in the Bozeman coal field. There is, therefore, very little reason for supposing that these aments belong to this genus.

On the other hand, these aments have a decided resemblance to the mature fruiting aments of certain living species of Populus. They are for example very like *Populus monolifera* Ait., and more particularly *P. Fremonti*, Wats., var. *Wislizeni* Wats., from the state of Chihuahua, Mexico, as preserved in the herbarium of the U. S. National Museum. The living species mentioned have long aments with the large capsules pediceled as in the fossil and they decrease in size from above downward in the same manner.

While no leaves of Populus have so far been obtained in the same beds with these aments, no less than three well-marked species have been found in other parts of the Bozeman coal field, thus showing that this genus was undoubtedly present. It is, however, open to question, and it is to be understood as a merely provisional name awaiting the possible discovery of new and more decisive material.

Salix angusta Al. Br.

The recent collections contain a great number of leaves or fragments of leaves which seem to be the same as those so identified by Lesquereux, but they are mostly without nervation and therefore in doubt.

Quercus chlorophylla Ung.

The specimens referred by Lesquereux are in the Museum collection and are found to have come from the coarse sandstone layer. They are very obscure with very little nervation. The specimens in the recent collection are also in the coarse sandstone and are equally obscure. They are, however, the same as those referred by Lesquereux to this species.

Quercus castanopsis Newberry.

This determination is based on a single fairly well-preserved leaf, and can not therefore be regarded as of much value.

[1] *Fl. foss. arct.*, VI, Nachträge z. Jura Fl. Sibiriens p. 18, Pl. VI, Fig. 15.

QUERCUS GODETI? Heer.

The specimens referred by Lesquereux to this species are in the Museum collection, while the later collections do not contain it.

QUERCUS ? FRAXINIFOLIA LX.

No additional specimens of this species have been seen.

QUERCUS ELLISIANA LX.

The most abundant species of oak found in the collections.

Quercus Pealei Lx., was founded upon a single leaf from Spring canyon. This specimen is fortunately preserved in the U. S. National Museum, and after some consideration I have decided to reduce it to *Q. Ellisiana*. Lesquereux in his last mention of *Q. Pealei* (Tert. Fl., p. 156) said: "This small leaf * * * may be referable to the former species." It comes from the same beds, and is the only one ever obtained. At first sight the nervation may appear quite unlike the typical *Q. Ellisiana*, but by comparing all the figures and recent specimens it is found that the position and direction of the lowest pair of secondaries depend upon the shape of the leaf, and the narrower examples of *Q. Ellisiana* have the same character.

JUGLANS RUGOSA LX.

A number of good specimens obtained.

JUGLANS DENTICULATA Heer.

No specimens observed in the recent collections, and none of those referred to this species by Lesquereux are in the Museum collection.

JUGLANS RHAMNOIDES LX.

The specimens referred to this species by Lesquereux are also missing, and none that could be regarded as similar have since been found.

PLATANUS GUILLELMÆ Göpp.

A number of well preserved leaves were found which seem clearly to belong to this species. They are evidently closely allied to the following species, as pointed out by Lesquereux,[1] and have usually been found associated with it. They probably represent a single variable species.

PLATANUS ACEROIDES Göpp.

None of the recent material contains specimens that seem to belong to this form, and its presence is based on Lesquereux's determination

[1] Tert. Fl., p. 183, et seq.

and upon a single broken specimen in the Museum collection under the name *Quercus platanoides*, now regarded as a synonym of *P. aceroides*.

FICUS AURICULATA Lx.

The recent collections contain nothing but a number of fragments that are doubtfully referred to this species, while the type specimens are missing.

FICUS TILIÆFOLIA Al. Br.

This species enjoys precisely the same status as the former.

FICUS PLANICOSTATA Lx.

The recent collections embrace a number of well preserved leaves that are referred with much certainty to this species.

CINNAMOMUM SCHEUCHZERI ? Heer.

The specimens in the collection of 1872 were doubtfully referred by Lesquereux to this species. They are preserved in the Museum collection and agree exactly with a number in the late collections. They are, however, not sufficient to settle the real question of their identity.

CINNAMOMUM ELLIPTICUM n. sp.

Cinnamomum polymorphum Al. Br., Lesquereux, Tert. Fl., p. 221, pl. XXXVII, fig. 10 [non fig. 6].

Cinnamomum Rossmässleri Heer, Lesquereux, Hayden's Ann. Rept., 1872, p. 379.

Leaf of medium size (about 9^{cm} long and 4^{cm} broad), long-elliptical in outline, apparently rounded above to a short acumen (broken), and below to a rounded, slightly wedge-shaped base; lateral nerves thick, as prominent as the midrib, ascending to near the upper extremity, branching outside; midrib sparingly branched above the middle.

Habitat: Hodson's coal mine on Meadow creek, 12 miles southeast of Bozeman, Montana.

It is with some hesitation that this species is described as new to science. It depends upon a single well preserved leaf and a number of more or less doubtful fragments. This nearly perfect specimen was described by Lesquereux as *C. polymorphum*, Al. Br., and is the only specimen upon which the presence of this abundant European species in American strata rests. In the discussion regarding *C. polymorphum*, Lesquereux says: "In the leaves[1] which I refer to this species, the surface is coarser cut by deeper nervils, the midrib more divided than in *C. affine*.[1] But the essential characters of *C. polymorphum* are not sufficiently distinct upon our specimens, none of them having the upper part of the

[1] *The other one of the two so referred is now placed under C. affine Lx. F. H. K.*

leaves or the acumen preserved, and the areolation and fibrillæ of the borders being obsolete. Therefore we may have in the two leaves referred here to *C. polymorphum* mere varieties of *C. affine*, and thus it may be that all the American Cinnamomum leaves represent only one species."

A careful comparison of the many published figures of *C. polymorphum* does not show any that agree satisfactorily with the one under discussion. It is for example much nearer to *C. Rossmässleri* Heer[2] with which Lesquereux appears at first to have identified it. It is also less like *C. affine* than he supposed it to be.

LITSEA WEEDIANA n. sp.

Tetranthera sessiliflora Lx. ex. p. Lesquereux, Tert. Fl. p. 217, pl. xxxv. fig. 9.

Leaf sessile?, entire, oblong-lanceolate in outline, broadest below the middle from which point it tapers upward gradually, then rather abruptly, into a sharp-pointed apex, and downward into a rounded heart-shaped base; midrib straight; secondaries about 6 or 7 pairs, subopposite, camptodrome, lowest pair emerging from just above the apex of the petiole at a more acute angle than the upper ones, joining the second pair just above the middle of the leaf; just below the first prominent pair of secondaries is a pair of thin veins that arch along near the lower margin of the leaf and unite with a branch of the first pair at about the middle of their length; cross nervation at right angles to the midrib.

Habitat: Hodson's coal mine on Meadow creek, 12 miles southeast of Bozeman, Montana.

The specimen of this species figured in the *Tert. Fl.* pl. xxxv, fig. 9, as *Tetranthera sessiliflora* was said by Lesquereux to have come from Evanston, Wyoming. Fortunately this specimen is still preserved in the U. S. National Museum collection (No. 305). A glance at the matrix shows conclusively that it could not have come from any known horizon at Evanston, and on referring to the Museum catalogue it is found properly recorded from "Spring canyon, Montana." The Museum contains another very perfect specimen (No. 834) of this species from the same place recorded under the name of Cassia, and the recent collection also affords another fine leaf, both of which agree perfectly with the one figured in the *Tert. Fl.*, loc. cit.

These leaves differ markedly from *Litsea* (*Tetranthera*) *sessiliflora* in being apparently sessile, in being broadest much below the middle, with a heart-shaped base and in having 6–7 pairs of secondaries with a single pair of thin veins below the lowest prominent pair. I have therefore regarded them as new to science and have named the species in honor of Mr. Walter H. Weed of the U. S. Geological Survey, who has done so much to unravel the intricate geology of this region.

[1] Fl. Tert. Helv. II, pl. XCIII, fig. 15.

LAURUS SOCIALIS Lx.

A number of fairly well preserved leaves are referred to this species.

FRAXINUS DENTICULATA HEER.

Several leaves with dentate margin are referred with considerable certainty to this form. It is, however, not well characterized.

ANDROMEDA GRAYANA HEER.

Probably the most abundant species from this locality.

ANDROMEDA AFFINIS Lx.

This species was first described by Lesquereux in Hayden's Annual Report, 1874, p. 348. It is there said to have come simply from "Spring canyon," without indication of the state or territory, and is included with the plants of the Dakota group. The type specimen is preserved in the U. S. National Museum where it was found among the specimens from Spring canyon, Montana, from which place it undoubtedly came as shown both by its original number and by the matrix in which it is preserved. In the Cretaceous and Tertiary Floras, p. 60, it is described among the Dakota group plants, an error which is also perpetuated in the final Flora of the Dakota Group, Monograph U. S. Geological Survey, XVII, p. 118.

NYSSA LANCEOLATA Lx.

The original specimens from Spring canyon that were referred by Lesquereux to this form are missing and none of the recent material contains it.

CORNUS RHAMNIFOLIA O. Web.

The specimens in the 1872 collection were preserved in the coarse sandstone and as they are very obscure they were with doubt referred to this species. The material from the mouth of the Bear canyon contains one or two leaves that have been referred here, although they are so obscure as to render their identification doubtful.

LEGUMINOSITES CASSIOIDES Lx.

A number of specimens are referred with certainty to this form as determined by Lesquereux's identification of the 1872 material.

CISSUS TRICUSPIDATA ? Lx.

Doubtfully referred to this species.

RHAMNUS RECTINERVIS Heer.

There are no specimens in the recent collections that can be referred to this form and the type specimens are also missing.

RHAMNUS SALICIFOLIUS ? Lx.

A number of fragments are doubtfully referred here.

CELASTRINITES LÆVIGATUS Lx.

The types of this species are preserved in the National Museum and are the only specimens ever found.

DOMBEYOPSIS PLATANOIDES Lx.

The types of this species are also to be found in the National Museum, and one or two fairly good additional specimens have been found.

NELUMBO.

A very obscure fragment doubtfully referred as above.

DISCUSSION OF TABLE.

Before passing to a consideration of the table it may be well enough to call attention to several points which would seem worthy of more consideration and weight than has usually been given them in many discussions of this kind, and in doing this I can hardly do better than quote from a recent paper by Prof. Fontaine.[1]

[1] Fossil plants from the Great Falls coal field, Montana. Proc. U. S. Nat. Mus. 1892, vol. xv, p. 489.

Table showing distribution of plants in the Bozeman coal field.

	Hodson's coal mine (Liv).[1]	Flathead pass (Liv).	Quarry, Chestnuts (Liv).	Mission creek (Liv).	Head of Fir Canyon (L).[2]	Mouth of Fir Canyon (L).	Mouth of Bear Canyon (L).	Craig & Horr mines (L).	Laramie (coal-bearing).	Denver.	Carbon and Evanston.	Fort Union.	Eocene (Alum bay, etc.).	Green River group.	Miocene.	Pliocene.	Remarks.
Anemia subcretacea (Sap.) Ett. & Gard.					×			×	×	×			×				
Aspidium Lakesii (Lx.) Kn									× ?	×							
Equisetum ?.				×													
Abietites dubius Lx	×			×	× ?			× ?	×								
Sequoia Reichenbachi Gein			×						×								
Taxodium dist. miocenum Heer	×										×	×		×	×	×	
Ginkgo adiantoides Ung				×								×	×		×	×	
Thinnfeldia polymorpha (Lx.) Kn					×												
Thinnfeldia lanceolota, n. sp					×												
Phragmites alaskana Heer	×	×	×									×		×	×		
Caulinites sparganioides Lx			×						×		×						A true Laramie species.
Populus mutabilis ovalis Heer	×								×		×				×		
Populus lævigata Lx	×									×							
Populus ? problematica, n. sp					×												
Populus cf. arctica Heer						×											
Salix angusta Al. Br	×	×			×								×		×	×	Tertiary, mainly Miocene.
Quercus chlorophylla Ung						×											
Quercus castanopsis Newb	×											×					
Quercus Godeti Heer	×																
Quercus fraxinifolia Lx						×	×										
Quercus Ellisiana Lx	×					×											
Juglans rugosa Lx	×								×	×	×	×	×	×	×		Has a wide distribution.
Juglans denticulata Lx	×									×	×			×	×		
Juglans rhamnoides Lx	×								×	×	×						
Platanus Guillelmæ Göpp	×				×		×			×							Miocene outside of United States; true Laramie in United States.

Platanus aceroides Göpp			× ?							×	×	×	×	×	×	×	Miocene species outside of United States.
Ficus auriculata Lx	×									×							Mainly a true Laramie species.
Ficus tiliæfolia (Al. Br.) Heer	× ?								×	×	×	× ?		×	×	×	Largely Miocene outside of United States; typical in California Miocene.
Ficus planicostata Lx	×			×					×	×			×				Mainly a Denver species.
Cinnamomum Scheuchzeri? Heer	×																
Cinnamomum ellipticum n. sp	×																
Litseà Weediana n. sp	×																
Laurus socialis Lx			×								×		×				Type from the Laramie.
Fraxinus denticulata Heer	×								× ?		×				×		Mainly a Miocene species.
Andromeda Grayana Heer	×				×			× ?							×		
Andromeda affinis Lx	×				×												Distribution by error; all Dakota group.
Nyssa lanceolata Lx	× ?									×							Denver only outside of Bozeman coal field.
Cornus rhamnifolia O. Web.							×										Identification doubtful; distribution omitted.
Leguminosites cassioides Lx					×			×						× ?			
Cissus tricuspidata? Lx				×					×	×							Identification doubtful.
Rhamnus rectinervis Heer	×								×	×	×				×		
Rhamnus salicifolius? Lx	×								×								
Celastrinites lævigatus Lx	×																
Dombeyopsis platanoides Lx					×												

[1] LIV = Livingston beds.

[2] L = Laramie beds.

After discussing at some length the facies of the Great Falls flora Prof. Fontaine says: "In this connection I will repeat an opinion expressed before. In determining the age of an unknown group of fossil plants, greater weight, as evidence of age, ought to be assigned some plants than others. These are the plants whose fossils have marked and salient features, that permit them to be identified without danger of error. An example of this kind is *Frenelopsis*, especially *F. parceramosa* of the Potomac flora. Where these are fully established and at home in a formation, as would be shown by their general distribution and the abundance of fossil specimens that they afford, they ought not to be considered as units in a sum total to establish a percentage. Their evidence would thus be neutralized by that of other units which are newcomers or belated survivors. This is especialy true of floras in a critical stage of evolution, and which contain a considerable number of newcomers and survivors. The Potomac flora was one of this character, in which Jurassic types were being cast out and Cretaceous ones introduced."

The Bozeman coal field presents a problem somewhat similiar to that of the Great Falls coal field and remotely of the Potomac formation. That is, the fossil plants play an important role in confirming the results of stratigraphy. But as Fontaine has said we should not take absolute percentages but should take into account the species which may be identified with absolute or at least reasonable certainty, and also their relative abundance. Several European species were identified by Lesquereux with hesitation in this flora, such as *Quercus Godeti*, *Cinnamomum Scheuchzeri*, *Rhamnus salicifolius*, etc., and it would manifestly be not only unwise but probably absolutely wrong to attach much weight to the foreign distribution of species of so doubtful a status. Such determinations are especially hazardous when, as in the present instance, the specimens are fragmentary or preserved in a matrix which will not retain the essential nervation.

Again, it would seem well to use with caution evidence derived from a single specimen of a species, no matter how certain its identification might be. It may be a waning type or a newly introduced one. The force of this argument, however, is somewhat reduced by the fact that, unless the exploration of the beds has been very thorough, we can never be certain that the specimens seen are a fair and full representation of everything found at that place. There is always the possibility that the next blow of the hammer may have revealed an abundance of what is now considered rare or perhaps represented by a single specimen.

Lesquereux, in his original consideration of this flora, referred it to the lower lignite[1] or true Laramie. Prof. Ward, on the other hand, inclined to regard it as belonging to the Fort Union[2] beds, but he in-

[1] Hayden's Ann. Rept., 1872, p. 409.

[2] Synopsis of the Flora of the Laramie group, p. 441.

cluded with the Bozeman coal field the somewhat indefinite localities in or near the Yellowstone National park, known as Yellowstone lake, Elk creek, and Snake river, therefore attaching undue weight to species common to these places and the Fort Union beds. The specimens that Lesquereux examined from these localities are fortunately nearly all preserved in the National Museum, and from a study of the matrix in which they are preserved, together with the recollections of Dr. A. C. Peale, who either collected them personally or was with the parties when they were obtained, we are able to arrive at a pretty definite conclusion as to their position. Those from the "Snake river," or rather from the "Divide between Snake river and Yellowstone lake," were collected by Dr. Hayden's party in 1871, and are from strata resting directly upon the Fox hills, therefore probably true Laramie. This view is confirmed by the present members of the U. S. Geological Survey connected with the Yellowstone park division. This is the type locality for *Gymnogramma Haydenii* or *Anemia subcretacea*, as it is now called.

The specimens from the Yellowstone lake were obtained during the same season by Dr. Hayden himself, and come from the west side of the lake, probably not far from Stevenson's peak. The material is the brittle shales, characteristic of what is known as the Volcanic Tertiary of that region. *Equisetum limosum?* Linn., was identified from this place.

The specimens from Elk creek were obtained by Dr. Peale, who is able to locate the spot very definitely on the present map of the Yellowstone park. They came from the foot of low bluffs just above (N. W.) the trail to Pleasant valley. That is, they came from the base of Crescent hill, about one mile above Yancey's. Several specimens were obtained here, among them *Platanus nobilis* or *Aralia notata*, as it was called by Lesquereaux, the species which Prof. Ward seems largely to have relied upon to establish their connection with the Fort Union beds.

Having disposed of the localities clearly confounded with the Bozeman coal field, we may turn to a consideration of the table of distribution. This table embraces 44 more or less satisfactory species, which composes the flora of these beds. Of this number 5 are regarded as new to science, and are, therefore, dismissed as having, in themselves, no diagnostic value or at most only negative value. Of the remaining, 11 species have so far never been found outside of these beds, thus leaving 28 species having a distribution, and upon which we must largely rely for comparison. Of these 28 species no less than 22 are confined to the Livingston beds, while only 2 are confined to the Laramie proper, and 4 are found in both Livingston and Laramie beds. With this distribution of species within the Bozeman coal field in mind, we may pass to a comparison with other floras.

Of the 28 species only 7 have been found in the Fort Union beds.

These are *Ginkgo adiantoides*, *Phragmites alaskana*, *Juglans rugosa*, *Platanus aceroides*, and *Taxodium distichum miocenum*, which are positively identified in the two horizons, and *Quercus castanopsis*, which depends upon a single broken leaf from Hodson's coal mine, and *Ficus tiliæfolia*, found only in fragments in both places. Of the first four species, *Ginkgo adiantoides* has a very wide distribution outside of the United States in the Miocene and Pliocene of Europe. *Juglans rugosa* was originally described[1] from Marshall's mine, near Denver, Colorado, and is also especially abundant in the Denver formations at Table mountain, Golden, Colorado. It has a wide distribution in the United States and has also been found in the English Eocene at Alum bay Isle of Wight.

Of the 22 species of the Livingston beds having a distribution outside of this area, we find that 4 species (*Populus lævigata*, *Juglans denticulata*, *Ficus auriculata* and *Nyssa lanceolata*) are confined exclusively to the Denver beds of Colorado; 3 species occur in the Denver and later formations; 3 species in Tertiary beds; 10 species in Denver and Laramie, and only 2 species (*Sequoia Reichenbachi* and *Rhamnus salicifolius*) in Laramie exclusively. That is, no less than 17 of the 22 species are found either exclusively in the Denver or have their greatest development in this formation.

Of the 4 species (*Abietites dubius*, *Salix angusta*, *Platanus Guillelmæ* and *Andromeda Grayana*) found in both Livingston beds and Bozeman-Laramie, *Abietites dubius* is of doubtful status, being questionable in the Bozeman-Laramie; *Salix angusta* is a common European Eocene and Miocene species and is not found in the Laramie outside of the Bozeman coal field; while the other two are clearly identified in both horizons.

The two species found in the Bozeman-Laramie exclusively are *Anemia subcretacea* and *Quercus chlorophylla*, the first depending on a few fragments and the second upon a single specimen.

As the localities of Carbon and Evanston, Wyoming, are still open to question as to their age, it has been thought best to keep up the distinction by placing them in a separate column. They were regarded by Lesquereux as belonging to his Upper Lignitic, and therefore possibly belong to what has since been differentiated as the Denver group, to which they have been referred in the above tabulation, although Dr. C. A. White[2] would probably regard them as true Laramie, as he considers the Arapahoe and Denver formations as contemporaneous with the upper part of the Laramie, *where it is complete.* A more thorough study of these localities in the light of present knowledge would undoubtedly be productive of important results.

The only group which it remains seriously to consider is the true Laramie or coal-bearing series of strata, the Lower Lignitic of Les-

[1]Hayden's Ann. Rept., 1869, p. 96.

[2]Bull. U. S. Geol. Survey, No. 82, p. 150.

quereux as typified at Raton mountains, New Mexico, Point of Rocks, and Black buttes, Wyoming, etc. Of the 28 species taken as the basis of comparison in the Bozeman coal field 14 have been found in the Laramie proper. This, it is to be understood, is the absolute number, of which several, from one cause or another are doubtful; thus, excluding the 2 species found only in the Laramie of both areas, and at least 5 of the 10 species above pointed out as common to the Denver and Laramie, we have no more than 6 or 7 of the 28 species belonging, in numbers worthy of much consideration, to the Laramie.

From these considerations it appears, beyond question, that the flora of the Livingston formation finds its nearest relationship with the flora of the Denver beds of Colorado. This result appears to differ from the results obtained by a preliminary study of this flora as set forth in a short paper published in July, 1892, on the *Fossil Flora of the Bozeman Coal Field.*[1] In that paper it was stated that an equal number of species were common to the Bozeman flora, and the Denver and Laramie of other parts of the United States. This statement was based on the distribution of the Laramie plants as contained in the books, which were published before the Denver beds had been separated as a distinct series, and when it was consequently impossible to tell exactly where a species came from, when as at Golden, Colorado, both formations are present, and both plant-bearing. Since that time much labor has been expended on a thorough revision of the Laramie and allied floras, based upon most of the original material, together with extensive recent collections. The result of this has been to fix definitely the distribution of a large number of the species, the horizon of which were before loosely given or often wholly unknown. This modification of our knowledge of distribution had made possible the above corrections in the working out of the affinities of the Bozeman flora.

NOTE.—Since the foregoing paper was written Mr. W. H. Weed has submitted to me a small collection of fossil plants obtained by him at the foot of the Crazy mountains, on Big Timber creek, Park county, Montana. The collection numbers nine specimens which I have been able to identify as follows: A single specimen each of *Sequoia Langsdorfii* Heer, and *Populus genatrix* Newberry, and four specimens of *Ulmus speciosa?* Newberry, with fragments of a *Platanus* (possibly *P. nobilis*), a *Phragmites* and *Ulmus* sp.

Sequoia Langsdorfii has been abundantly found in, but is not confined to, the Fort Union group, while *Populus genatrix* and *Ulmus speciosa* are typical Fort Union plants. While it is manifestly unsafe to place much dependence in such meager data all the species identifiable belong to or are found in the Fort Union group.

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[1] Proc. Biol. Soc., Wash., vol. VII. pp. 153, 154.

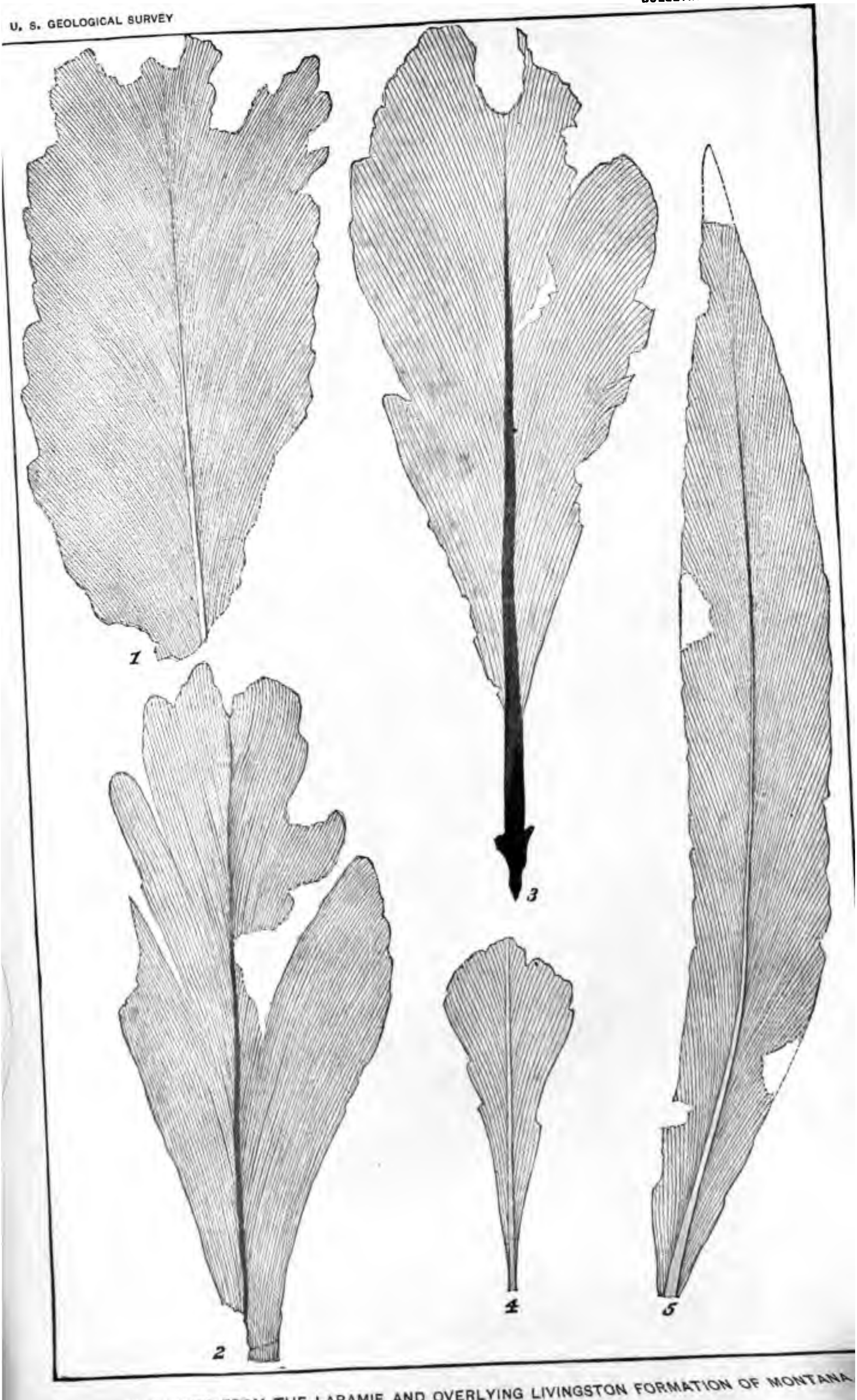
Plate V.

Figs. 1–4. *Thinnfeldia polymorpha* (Lx.) Kn.

From head of Fir canyon, 8 miles east of Bozeman, Montana.

Fig. 5. *Thinnfeldia lanceolata* n. sp.

From head of Fir canyon, 8 miles east of Bozeman, Montana.



FOSSIL PLANTS FROM THE LARAMIE AND OVERLYING LIVINGSTON FORMATION OF MONTANA

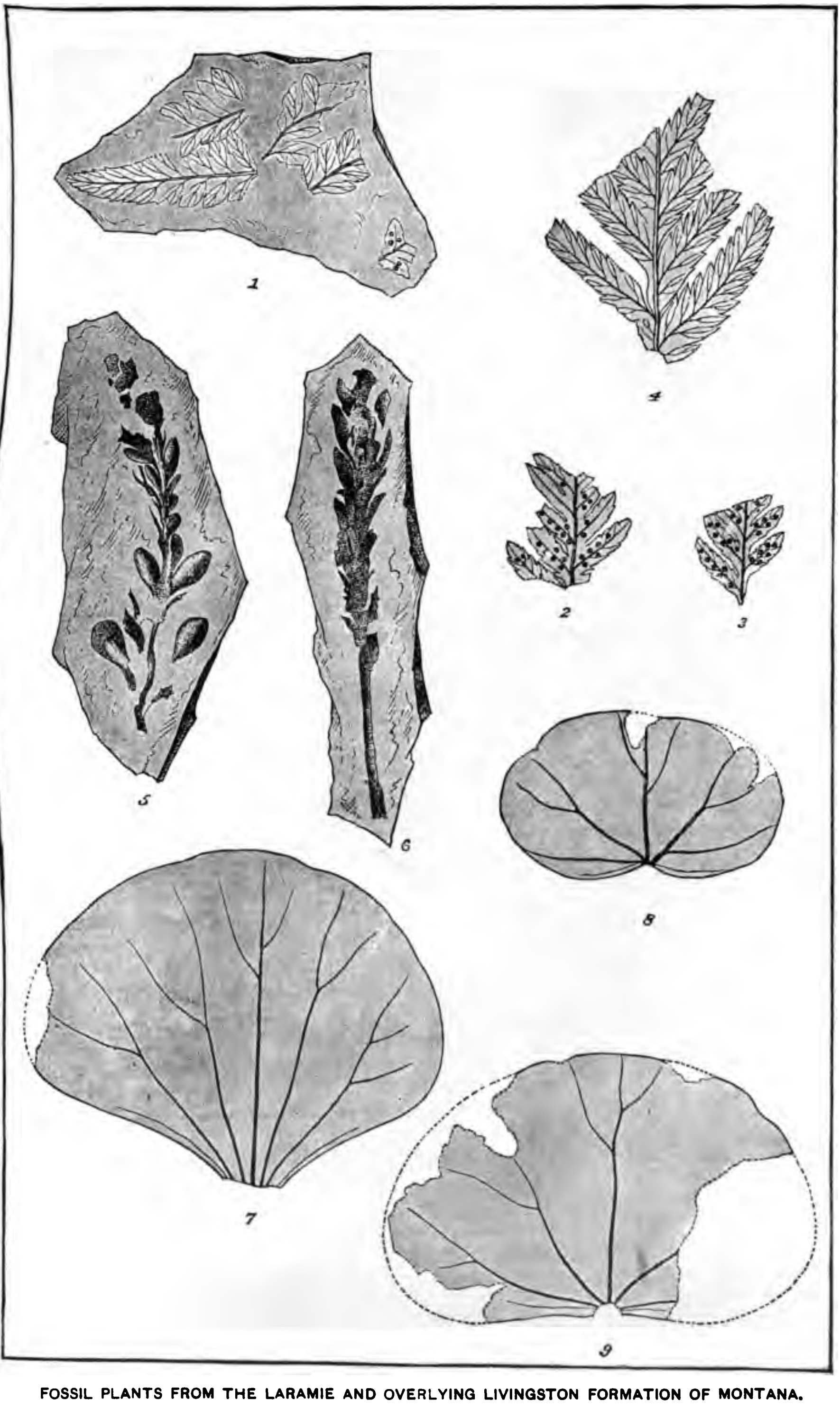
PLATE VI.

FIGS. 1–3. *Aspidium Lakesii* (Lx.) Kn.
From point between Middle and North branches of Bear creek, east of Madison valley, Montana.

FIG. 4. *Aspidium Lakesii* (Lx.) Kn.
From Quarry No. 2, 3,000 feet east of the Douglas coal mine, Sedalia, Colorado. (Introduced for comparison.)

FIGS. 5, 6. *Populus ? problematica* n. sp.
From head of Fir canyon, 8 miles east of Bozeman, Montana.

FIGS. 7–9. *Populus* cf. *arctica* Heer.
From near mouth of Bear canyon, 6 miles southeast of Bozeman, Montana.



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